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Assessment on carbon footprint of steel frames for building structures

Master's thesis for the degree of Master of Science in Engineering submitted for inspection.

Espoo 23.11.2020
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Abstract of master's thesis

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Abstract

Life Cycle assessment method is currently used to assess the carbon emissions coming from buildings. The Finnish Ministry of the Environment aims to include the carbon assessment as a part of building's preliminary design. However, these new assessment guides exclude the contributions from connection components in the load-carrying frames. Moreover, with the improvement of operational energy efficiency, the impact of embodied carbon emissions has relatively been creased, thus lead to encourage the use of timber over steel for building structures.

Although more studies have focused on the emissions of structural materials, few studies have attempted to evaluate the combined effects of different static models on carbon emissions. Especially buildings with large open spaces are often built with frames consisting of columns and beams.

This study aimed to determine the contribution of the frame types to the total carbon footprint of the steel framed building structures. The thesis focused on three types of building frames: a pinned, rigid, and semi-rigid frame. The goal was to determine the options available to a designer when prioritizing the lowering of emissions for the whole structure. The frames were modelled from steel members with typical configurations, such as truss structures in long spans and single beams in shorter spans. Additionally, a wooden frame was modelled for a reference point of total carbon emissions for the steel frames.

Results show that frame types contribute more to the carbon emissions of a structure and therefore were relevant part in lowering of carbon emissions. In the models used in this thesis, frames with mast columns and pinned beam connections performed better than the other frame types. Whereas the studied semi-rigid frames had the highest carbon emissions compared to other two frame types. Moreover, in comparison of member types, frames made of open profiles performed better than the ones made of tube profiles of higher steel strength. The studied steel frames had 2.66 times higher emissions in average compared to the studied wooden frames, when the operating time of the structures was set to 100 years. In addition, connections are proved to be responsible for 13-33 % of carbon emissions of the studied frames.

Keywords Carbon footprint, LCA, EPD, GWP, Steel structure, Steel frame.

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Diplomityön tiivistelmä

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Tiivistelmä

Elinkaariarviointimenetelmää käytetään tällä hetkellä rakennusten hiilipäästöjen määrittämisessä. Suomen ympäristöministeriön tavoitteena on sisällyttää hiiliarviointi osaksi rakennuksen alustavaa suunnittelua. Tässä uudessa arviointimenetelmässä ei kuitenkaan oteta huomioon rakenteiden kiinnitysosia. Lisäksi menetelmän uskotaan suosivan rakenteissa puun käyttöä teräksen sijaan.

Vaikka rakennemateriaalien päästöjä on tutkittu paljon, aikaisemmissa tutkimuksissa ei ole yritetty arvioida erilaisten staattisten mallien vaikutuksia hiilipäästöihin. Etenkin rakennukset, joissa on suuret avoimet tilat, rakennetaan usein pilareista ja palkeista koostuvista kehistä. Kehät voidaan luokitella staattisen mallin mukaan. Staattinen malli eroaa kehyksen reunaehtojen suhteen. Kappaleen (ts. pilarin tai palkin) päädyt voidaan kiinnittää joko jäykästi tai nivelellisesti. Jäykässä kiinnityksessä kappaleen pää ei pääse kiertymään, kun taas nivelliitos sallii kappaleen kiertymisen. Kahden rajaehdon lisäksi insinööri voi suunnitella kiinnitykset puolijäykiksi, mikä sallii jonkin verran kiertymistä ilman, että se olisi kokonaan jäykkä tai nivelellinen.

Tämän tutkimuksen tarkoituksena oli selvittää runkotyyppien vaikutus rakennuksen hiilijalanjälkeen. Opinnäytetyössä keskitytttiin rakennuksen kolmeen rakennemalliin: nivelellinen, jäykkä ja puolijäykkä kehä. Tavoitteena oli määrittää suunnittelijan käytettävissä olevat vaihtoehdot vähähiilisessä rakentamisessa. Kehykset mallinnettiin teräsosista tyypillisillä ratkaisuilla, kuten ristikkorakenteilla pitkillä jänneväleillä ja yksittäiset palkit lyhyemmillä jännevälillä. Lisäksi puurunko mallinnettiin teräs- ja puurunkojen välistä vertailua varten.

Tulokset tukivat ajatusta siitä, että kehätyypit vaikuttivat rakenteen hiilipäästöihin ja olivat siten merkityksellinen osia hiilipäästöjen vähentämisessä. Tässä opinnäytetyössä käytetyissä malleissa mastopilari kehä nivelellisillä palkkiliitännöillä toimivat paremmin kuin muut kehätyypit. Puolijäykillä kehillä oli korkeimmat hiilipäästöt verrattuna kahteen muuhun kehätyyppiin. Avoimista profiileista valmistetut kehät toimivat paremmin kuin korkeamman teräslujuuden omaavat putkiprofiilit. Teräsrunkojen päästöt olivat keskimäärin 2,66 kertaa suuremmat kuin puurunkoisten kehien, kun rakenteiden käyttöaika asetettiin 100 vuoteen. Lisäksi kiinnitysosat olivat vastuussa 13–33 % kehän hiilidioksidipäästöistä.

Avainsanat Hiilijalanjälki, LCA, EPD, ympäristöseloste, GWP, Teräsrunko, Teräskehä, vähähiilinen rakentaminen.

Preface

This study was based on a personal interest in learning the causality between structural design and environmental impacts. I hope I contributed to the future development of carbon assessment and sustainable design.

I want to thank those who shared the same enthusiasm as me and helped me succeed with my study. I want to thank Dr. Lu for supervising my thesis and always being ready to help me. Many thanks to Ramboll for funding and supporting this study. I want to thank my advisors Inkala (M.Sc.) and Majoinen (M.Sc.) for giving me good insight on what to consider in my study. I want to thank Dr. Pennington for helping with the structure of the thesis, and I also want to thank my friends Ahmed (M.Sc.) and Lopatinski (M.Sc), for giving tips on how to proceed with the thesis. I would like to thank Dr. Haapio for carving the path for assessment of steel structures and helping me on technical parts. And lastly, I want to thank Ms. Favale (M.Sc) for supporting me through the entire thesis.

Espoo 23.11.2020

Eres Berki

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Notations and nomenclature

Statistics

e		Estimated margin of error
n		Sample size
p		Relative frequency calculated from the sample
$z_{0.95}$		Critical value associated with the level of confidence

Stiffness calculation

E	[MPa]	Young's modulus of elasticity
k_i	[mm]	Strain factors for components in connection
$S_{j.ini}$	[MNm/rad]	Rotational stiffness in elastic area
S_j	[MNm/rad]	Rotational stiffness when upper limit of elastic area is surpassed
Z_g	[mm]	Distance from gravitational neutral axis of a profile
η		A correcting factor from EN1993-1-8

Frame design

D	[kN/m^2]	Pressure formed against a wind and internal under pressure
E	[kN/m^2]	Suction on the back of the building with internal overpressure
$k_{cr.y}$		Effective length factor about y-axis
$L_{cr.y}$	[m]	Effective length about y-axis
M_{Ed}	[kNm]	External moment
$M_{j.Rd}$	[kNm]	Moment resistance of the connection
$M_{j.Ed}$	[kNm]	External moment in the connection
$N_{y.Ed}$	[kN]	Axial load
$N_{y.Rk}$	[kN]	Axial resistance
q	[kN/m]	Line load applied to a member
σ	[MPa]	Internal stress
λ		Factor for slenderness
χ		Factor for axial buckling of a member in EN1993-1-1
χ_{LT}		Factor for lateral torsional buckling of a member in EN1993-1-1

Abbreviations

Sustainability	
BAT	Best Available Technique
BAU	Business as Usual
BREEAM	British Building Research Establishment Environmental Assessment Method
CO2eq	Carbon dioxide equivalent
DGNB	German Sustainable Building Council
EPD	Environmental Product Declaration
GBC	Green Building Council
GHG	Greenhouse Gas
GWP	Greenhouse Warming Potential
IPCC	The Intergovernmental Panel on Climate Change
LCA	Life-Cycle Assessment
LCC	Life-Cycle Costing
LEED	North American Leadership in Energy and Environmental Design
WLC	Whole-Life Costing
ÖKOBAUDAT	Standardized database for ecological evaluations of buildings by the Federal Ministry of the Interior
Manufacturing technology	
BF	Blast Furnace
CLT	Cross Laminated Timber
CSE	Classification System Equivalence
EAF	Electric Arc Furnace
GL	Glue Laminated Timber
HEA	Standardized H-shaped profile
HEB	Standardized H-shaped profile
IPE	Standardized I-shaped profile
MUF	Melamine Urea Formaldehyde
RHS	Rectangular Hollow Section
SHS	Square Hollow Section
Design	
BIM	Building Information Model
FEM	Finite Element Method
EN	Euro Norms
EN3	Euro Norms 1993 for steel design
EN4	Euro Norms 1994 for composite structures
NA	National Annex
RFEM	A FEM program by Dubal
SLS	Serviceability Limit State
ULS	Ultimate Limit State

1 Introduction

In the past decade, interest in lowering carbon emissions in buildings has grown, due to environmental concerns. Governments have required industries to evaluate the emissions of their products and construction companies to assess the emissions of their building projects. The Finnish Ministry of the Environment released their Life Cycle Assessment (LCA) method in Autumn 2019 to guide industry in evaluating carbon emissions of their products. However, this new assessment method does not consider connecting parts of building structures. Moreover, since the method focuses on only embodied carbon emissions of a material, it encourages the use of timber over steel for building structures. Considerable work has been devoted to assessment of the LCA method. Many studies have evaluated a single member (Varis, 2019, Alhola, 2015, Virmavirta, 2014, Hauke et. al. 2016) or a single building. (Johnson et. al. 2017, Emami et. al. 2019, Viljakainen & Lahtela, 2019, Haapio, 2013). However, none of these studies have considered the carbon emission of combined effect of members. Moreover, these studies statistically would require a larger data to determine the validity or reliability of the LCA method. No studies have attempted to determine the carbon emissions in terms of frame types.

Buildings with large open spaces are often built with frames consisting of columns and beams. Frames can be categorized according to their static model. The static model differs in terms of the boundary conditions of the frame. The boundary conditions of a member (i.e., a column or beam) can be either fixed or pinned. In a fixed connection, the end of a member has restrained rotation, while a pinned connection allows rotation of the member. In addition to the two boundary conditions, an engineer can design connections as semi-rigid, which allows some rotation without being entirely pinned or fixed. Although much work has focused on the emissions of structural materials, none of these studies have attempted to evaluate the carbon emissions determined by different static models (referred to herein as "frame types") on these emissions.

Therefore, this study aims to determine the effect of the frame type to the total carbon footprint of the building structure. This will be achieved by modeling three frame types at different span lengths and comparing the emission results in order to enable sustainable development of building structures. The thesis will focus on three frame types of a building: a pinned, rigid, and semi-rigid frame. The goal is to determine the options available to a designer when prioritizing the lowering of emissions for the whole structure. The frames will be modeled from steel members with typical solutions, such as truss structures in long spans and single beams in shorter spans. Additionally, a wooden frame will be modeled as reference for comparing steel and wood frames.

This thesis does not include double joint arc or three joint frames. The models consider only single level hall type structures. The design of frames is based on Eurocode 1993-1-1, 1993-1-8 and 1995-1-1. The frames do not consider fire design or accidental loading. The emission calculations consider Cradle to Grave modules A1-A5, C1-C4 and module D.

The remainder of this thesis is divided into 5 chapters. Chapter 2 reviews the literature of sustainability of building materials, LCA method, concepts of handprint and circulation economy and lastly the lowering of carbon emissions in steel frames. Chapter 3 describes the modeling of the frame types and the assessment for carbon emissions of each sub-parts of the frame. Chapter 4 presents the results of each frame type as total carbon emissions and the emission sources. Chapter 5 concludes the thesis and the results.

2 Literature review

The literature review consists of previous studies, research, articles and reports regarding the sustainability and carbon footprint assessment. This chapter is divided into sections, each section describes the main key elements or concepts regarding on how to assess carbon footprint.

2.1 Greenhouse gas and carbon dioxide equivalent

In current knowledge, greenhouse gas (GHG) is responsible for sustaining the constant temperature of the atmosphere. It consists of several substances, of which steam is the main ingredient (Mayors Indicators, CO_2-report 2018). An air with higher temperature can carry larger quantity of steam, which contributes to global warming. Second most common GHG is carbon dioxide CO_2, which contributes to the temperature of the climate in its feedback system. Feedback system of carbon consists of forests and seas, which produces and intakes the same amount of CO_2 to the atmosphere. However, carbon emissions that are caused from human activity are categorized as greenhouse warming potential (GWP). According to CO_2-report, 80 % of GWP gases are CO_2 of which 75 % are assumed to originate from fossil-fuels CO_2-report (2018).

All human caused pollutions that contribute to the GWP are equated to carbon dioxide equivalent CO_{2eq}. The conversion makes the different type of emissions into comparable unit. Each substance has its own conversion factor as shown in Table 2-1. The most significant greenhouse warming gases are fossil carbon dioxide (CO_2), methane (CH_4) and dinitrogen monoxide (N_2O). (Behm et al. 2016, p. 14.)

Table 2-1 Conversion factors for CO_{2eq}. (Behm et al. 2016 p. 14.)

	Conversion factor by IPCC
Carbon dioxide, CO2	1
Methane, CH4	25
Dinitrogen monoxide, N2O	298

2.2 Sustainability in Eurocodes

Environmental friendliness has a lot to do with the concept of sustainability, which plays an important role when building a framework for how the environmental impacts are evaluated. There are different interpretations for what sustainability includes. The EN 15978 delimit sustainability into five areas based on integrated building performance. The assessed areas are sustainable society, economy, and environment. EN 15978 mentions also technical and functional performances but does not provide framework for their assessment. Outside the Eurocode's scope, the sustainability focuses on how raw materials must be obtained from nature and how to release them back without causing permanent damage either to the environment or to the society.

The term 'sustainable' was first used in forestry to convey the idea that only as many trees could be felled in a given time period, as were capable of growing back. The concept was introduced to United Nations in 1987 and applied for environmental protection in 1992. (Hauke et al. 2016, p. 1-2.)

According to Hauke et al. (2016, p. 2) sustainability concept is formed by the interrelation of the environment, the society and the economy as shown in Figure 2-1. The sustainability in the building sector not only considers environmental impacts, but also economic growth and promote sustainable management of natural resources when rising basic standards of living. The concepts were discussed in Earth summit at Rio +20 Conference.

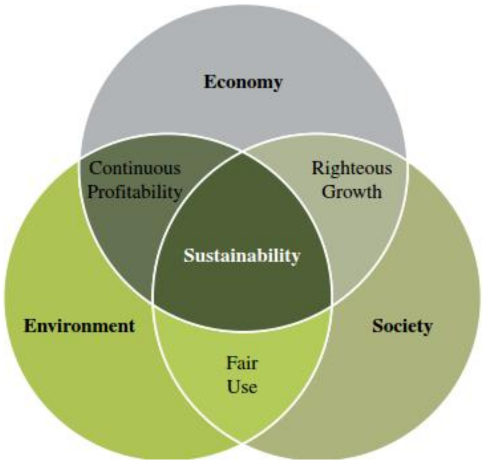

Figure 2-1 Three pillars of sustainability (Hauke et al. 2016, p. 9)

Sustainability consist of several sub-areas, which are all entangled together. This means that neglecting one can affect the others. For instance, ignoring the cultivation of trees would result in deforestation or excessive excavation of raw materials for steel could be reduced by recycling. It is also important to realize that any regulations that are made to help build better sustainable systems must be robust enough to allow humans to operate freely without damaging economic or social demands.

A sustainable timber industry must consider the economic benefits of felling trees and selling timber, while also being able to cultivate trees and use renewability of wood as a source of future income, thus being continuously profitable. Steel on the other hand is not renewable material and excavating raw coke has its limits on where and how much can be extracted. Recycling of steel reduces the need for excavation of raw material, which contributes to sustainability in social and environmental aspects, thus belonging to fair use category.

Ranta-Aho (2019, p. 18) highlights in his study the ecology of the substances, according to him there are four rules that cannot be neglected:

1. All the organisms live in the same ecosphere. What affects one, eventually affects all the others.
2. Everything must go somewhere. Nature does not know the concept of waste, and nothing can disappear.
3. The absence of something in nature is often a sign that the substance is incompatible with the nature.
4. Damage to nature often comes at a price and the price can be significant.

Ranta-Aho also points out that current regulations oblige that energy and natural resources are used sparingly. In construction industry focus is on lowering CO_{2eq} emissions throughout the buildings lifespan. Despite the enormous environmental impact of construction industry, construction is not truly instructed to become sustainable. (Ranta-Aho, 2019, p 20-21.)

Ecological sustainability requires placing human activities within the limits of nature's carrying capacity so as not to endanger biodiversity or the functioning of the ecosystem (Varis 2019, p. 10). Therefore, organizations have thought of ways on how to define and measure environmental impacts. An essential part is to be able to quantify data, from which conclusions can be drawn. Then the collected evidence can give a warrant for new policies.

Lice-cycle assessment (LCA) which is presented in EN 15978 provides a framework for manufacturers and building industry on how to assess the environmental, social, and economic performances, see Figure 2-2. Environmental performance is divided into three categories, Framework, building, and product level. Environmental performance in EN 15804 quantifies environmental impacts, resource usage, wastes, and output flows of products.

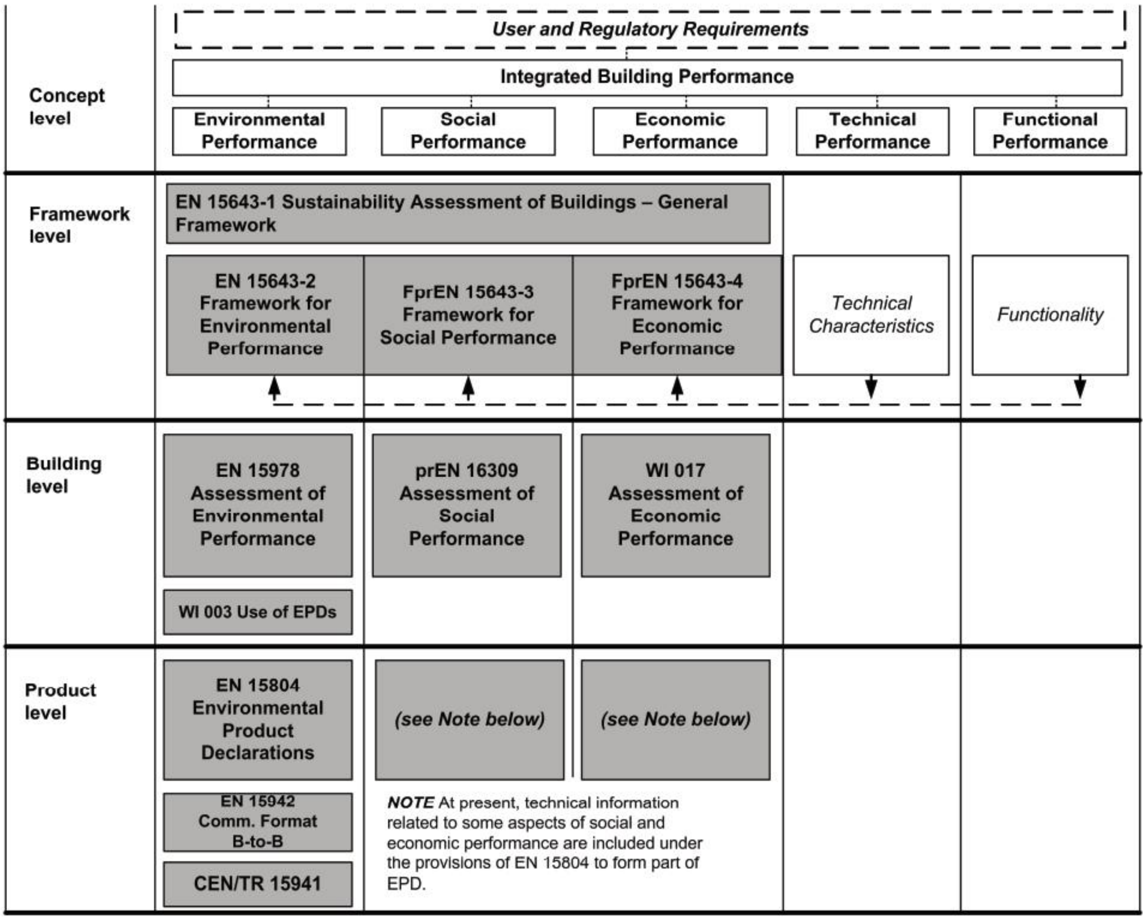

Figure 2-2 Framework for sustainability according to EN 15978.

2.3 Greenhouse warming potential in environmental product declarations

Environmental impacts of products are presented in environmental product declaration (EPD) reports. The environmental impacts are defined in EN 15978, see Table 2-2. The environmental indicators are GWP, but also six other such as acidification potential or eutrophication potential. The unit for GWP is defined as kg CO_{2eq} which is used when assessing embodied carbon of a product.

Table 2-2 Indicators describing environmental impact according to EN 15978 Table 2, p. 43

Indicator	Unit
Global warming potential, GWP	kg CO_2 equiv
Depletion potential of the stratospheric ozone layer, ODP;	kg CFC 11 equiv
Acidification potential of land and water; AP;	kg SO^{2-} equiv
Eutrophication potential, EP;	kg $(PO_4)^{3-}$ equiv
Formation potential of tropospheric ozone photochemical oxidants, POCP;	kg Ethene equiv
Abiotic Resource Depletion Potential for elements; ADP_elements	kg Sb equiv
Abiotic Resource Depletion Potential of fossil fuels ADP_fossil fuels	MJ, net calorific value

The embodied carbon of a building product is assessed in Environmental Product Declaration (EPD). The EPD reports can have boundary of product stages which are either limited to a ‘Cradle to Gate’ or to a ‘Cradle to Grave’ (EN 15978, 2012, p. 31). Cradle to Gate consists of embodied carbon of a product before the operation time defined as production stage, while Cradle to Grave includes all the stages in building life-cycle information.

In LCA the GWP related to a product is subdivided into life stages. Each life stage represents a source of emissions which are production stage, construction process stage, use stage, and end-of-life stage. Each life stage consists of modules shown in Table 2-3.

EPD reports can be of five different types according to EN 15804 (2012, p.13). These types are defined based on presented information. Product stage consists of modules A1-A3, which are mandatory in every EPD. Cradle to Gate type EPD’s include Modules A1-3 and optionally modules C1-4, whereas Cradle to Grave must have information for every module (EN 15804, 2012, p.12-15). Modules A4-A5 are depend on the location of construction site and on machinery used for installment of the product. In a case where product requires regular maintenance or replacement, the modules B1-B7 must be included into EPD. Comparisons between construction products with or without an EPD must always be conducted within the context of their application in the building. (Hauke et al, 2016, p 16.)

Table 2-3 Modules and descriptions of each stage of LCA. (Hauke et al, 2016, p 16.)

Building Assessment Information				
Building Life-Cycle Information				
Product Stage	**Construction Process Stage**	**Use Stage**	**End-of-Life Stage** (Building)	**Benefits and Loads** Beyond Building Boundaries
A1: Raw Material Supply A2: Transport A3: Manufacturing	A4: Transport A5: Construction–Installation Process	B1: Use B2: Maintenance B3: Repair B4: Replacement B5: Refurbishment B6: Operational Energy Use B7: Operational Water Use	C1: Deconstruction C2: Transport C3: Waste Processing For Reuse, Recovery and Recycling C4: Disposal	D: Reuse–Recovery–Recycling Potential

Beside environmental impacts, there is also a concept of life-cycle costing (LCC) for economic aspects. The LCC includes costs coming from construction, maintenance, operations, and end of life disposal. These are economical features of a product. Moreover, there is also a concept of whole-life costing (WLC), which considers indirect costs such as operational costs from leasing, taxes and rent income (Hauke et al, 2016, p 50). To support sustainable economic growth, companies should emphasize on enhancing positive impacts, rather than focusing on reducing negative impacts (Alvarenga et al. 2020, p 1). Therefore, LCA of environmental impacts needs to have synergy with other aspects of sustainability. However, the Ministry of the Environment started a process for forming new regulations for low carbon construction. Currently the aim is to include only the LCA as a part of preliminary design. A trial version of LCA-method for Finnish construction industry was released with the following schedule:

- 8/2019 – Low carbon assessment method version 1 is published
- 9/2019 – Pilot assistance search and piloting begins
- 6/2020 – Piloting stage ends
- 12/2020 - Emission database and assessment method version 2 completed
- 2021 – Piloting continues
- 2025 – New regulations come into effect

The assessment is meant to be done during the early design phase. The regulation instructs to make quantity lists based on Building 2000 Classification System Equivalence (CSE), which is a nomenclature used to classify parts and facilities of the building in design guidelines. The Building 2000 CSE nomenclature is familiar to construction companies in Finland. Unlike the Building 2000 CSE the new LCA guide provided from the Ministry of the Environment does not consider fastening components as it can be seen in
Table 2-4 or in Table 2-5. (Kuittuinen 2019, p. 12 & 17.)

Table 2-4 Building parts included in low carbon assessment (Kuittinen 2019, p. 18).

	Included in the analysis	Not included in the analysis
Site	+ Ground elements + Soil stabilisation and reinforcement elements– + Paved areas + Site structures	- Site equipment - Vegetation - Climate impacts of vegetation, soil or bodies of water
Load-bearing structures	+ Foundations + Ground floors + Structural frame + Façades, doors and windows + External decks + Roof structures	- Separate nails, screws, adhesives, seals, caulks and other fasteners, brackets, etc. that do not come with the products.
Supplementary structures	+ Interior walls and doors + Stairs + Surfaces + Normal fittings + Ducts and fireplaces + Prefabricated units	- Surface materials and mouldings - Surface treatment and paintwork - Separate nails, screws, adhesives, seals, caulks and other fasteners, brackets, etc. that do not come with the products.
Building systems	+ Heating systems + Water and drainage systems + Air conditioning systems + Cooling systems + Sprinklers + Electrical systems + Lifts	- Information systems - Building automation - Emergency power systems - Escalators - Separate machinery and equipment
Construction site	+ Energy consumed on the construction site	- Scaffolding and protective covers - Temporary structures, moulds and technical equipment - Life cycle of construction site facilities - Site personnel traffic

Table 2-5 Parts of building assessed in the LCA according to the Finnish Ministry of the Environment (Kuittuinen, 2019, p. 38). (Note, only top part of the original table presented)

Parts of a building assessed	*Assessed*	*Not assessed*
Site	Earth works, soil stabilisation and reinforcement elements, paved areas, site structures	Site equipment, vegetation, soil and bodies of water
Load-bearing structures	Foundations, ground floors, structural frame, façades, doors and windows, external decks, roofs	Separate fasteners
Supplementary structures	Interior walls, doors, stairs, surfaces, fittings, ducts and fireplaces, box units	Mouldings, surface materials and surface treatments, separate fasteners

2.4 Handprint and circular economy of building materials

Building assessment information includes module D, which represents the net benefits relating to exported energy, secondary materials, secondary fuels, or secondary products resulting from reuse, recycling, and energy recovery that take place beyond the system boundary (EN 15978, 2012, p.20.) Furthermore, the standards of LCA only provide the instructions to assess these environmental benefits. However, it does not provide clear instructions on how to assess these environmental benefits. Industries and individual organizations have developed their interpretation of how to quantify these environmental benefits.

In a similar way as carbon footprint represents the increased impact to greenhouse gasses, the concept of carbon handprint represents the reduced release of CO_{2eq} emissions, carbon capture, and carbon storage (Pajula et al., 2018, p.8-10). However, the way timber industries portray handprint is very different compared to how steel industries portray it, as one focuses on renewable materials and in binding biogenic carbon while the other in recycling and reuse of the material.

Handprint refers to what good the society does for the environment. Norris (2015, p. 3) presents a perspective, where handprint is 'the good we do' in ways that are consistent with our measurement of the harm we cause. According to him, there are two ways to create a handprint:

- Preventing/avoiding footprints that would otherwise have occurred (this includes reducing the magnitude of footprints that occur, relative to what their magnitude would otherwise have been)
- Creating positive benefits which would not otherwise have occurred.

The benefits are considered when compared to business as usual (BAU). If business is reducing carbon footprint relative to BAU, the difference can be interpreted as a handprint (Norris, 2015, p 6). Norris also introduces concept of net positive value, where positive factors are equal or bigger than negative emissions.

Alvarenga et al. (2020, p. 1-3.) agrees with Norris (2015) that handprint can be received as benefit that would have not occurred otherwise. They also proposed to define environmental benefits into direct, indirect, and relative handprint. The direct way to increase handprint is by preventing or avoiding footprint emission that would otherwise have occurred. For example, replacing energy source in manufacturing from fuel-based to renewable can have a direct impact on CO_{2eq} emissions. Alternatively lowering of emissions can be achieved by using materials, that cause less CO_{2eq} emissions in process.

According to Behm et al. (2016, p. 4) Handprint was created to be a symbol of measure for commitment to positive action towards sustainability. Here handprint was observed from the economic viewpoint were advancements in technology or business model had benefits in the long run. Therefore, standardization should be included as a part of the process and trying to steer business towards better sustainability. Ideally expanding the knowledge of one's environmental effect can help control excess consumption or encourage to utilize side products. In this context the handprint can lead to better profitability in long term. (Behm et al. 2016, p. 15). The lower emissions compared to BAU gives advantage when company can meet growing demand of sustainable products.

Commonly handprint is calculated as saved material or reduced fossil fuel emissions (Kuittuinen, 2019, p. 27). The Finnish Ministry of the Environment accepts benefits such as reused and recycled materials, carbon sinks and carbon storages and energy production in handprint assessment (Kuittinen 2019, p. 34). Carbon sinks are systems that bind carbon into itself, such as seas, planted forests or chemical reactions like carbonation of concrete. According to instructions of the Ministry of the Environment, 50 % of the mass of the wood can be considered as handprint. Wood material stores carbon within, while making room for new renewable forests to grow and bind carbon from air.

Metsä Group released an article proclaiming that without the felling of trees, forests would release stored carbon back to the atmosphere. Moreover, unharvested trees lose the potentiality to be used as timber. Wood products can be interpreted either as short- or long-time carbon storages. (Kimmo, article, read: 17.06.2020).

Oiva (2019, p. 26) enforces that timber products can be considered as carbon storage. Wood utilize carbon dioxide when it grows, thus storing it. In average wood stores 1000 kg of carbon dioxide for every cubic meter of wood product. Stored carbon stays in the material during the time when raw material is used as timber. While allowing new stand to grow and store carbon. The same fact was used to make a warrant to claim the importance of forestry and usage of wood in construction by Varis (2019, p. 20), see Figure 2-3.

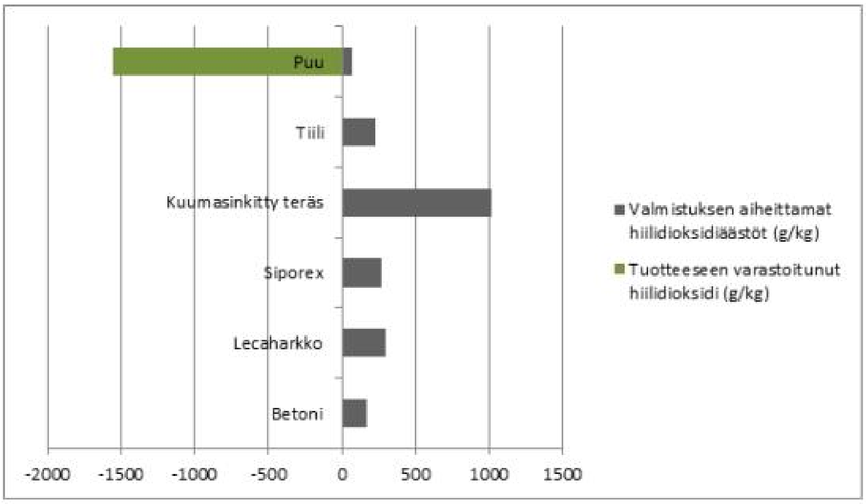

Figure 2-3 Footprint and handprint of wood (puu), brick (tiili), hot dip galvanized steel (kuumasinkitty teräs), lightweight concrete blocks (Siporex, Lecaharkko) and concrete (betoni). Handprint marked as negative value and footprint as positive. (Varis 2019, p. 20).

Based on current regulations, wood materials have superior net positive value compared to other materials. Beside the net positive value, scope of what is considered in regulations are unfair towards other structure materials. Accepting wood as carbon storage has been disregarded in many studies, rationalizing that forests are carbon storages rather than carbon sinks. A fully-grown forest emits and binds same amount of carbon to and from the atmosphere. Therefore, cutting down trees causes carbon debt. (Koskinen 2018, p. 66). In practice, the wood product is often burned in the end of its lifecycle, releasing the stored carbon back to circulation, this should invalidate the concept of carbon storage especially when considering the entire lifecycle of a product. (Virmavirta, 2014, p. 25).

In LCA trial version conducted by the Ministry of the Environment in 2019 gives following instructions for assessing the handprint:

- If materials are used in energy production, include the benefit coming from it in module D (p. 17)
- Transportation load utilization should be fixed to 80 % and return at 0 % (p. 23)
- Calculate used fuel and energy on the site (p. 27)
- Emissions coming from unused materials (p. 27)
- Evaluate benefits from using recycled materials and carbon storages (p. 30)
- Cutting of trees does not harm forests (p. 31)
- 50 % of dry timber weight is accepted as carbon storage (p. 32)
- Combine all the handprints together (p. 34)
- Do not reduce handprint from footprint (p. 34)

Substituting fossil fuels is counted as a benefit to GWP in EPD-reports. Released CO_{2eq} into atmosphere must be presented in module C3. Burning the wood products in the incineration facility can be thought to replace some of the fossil-fuels. However, the gained energy is not free of CO_{2eq}, even though the Ministry of the Environment categorizes the benefit as renewable energy (Kuittuinen 2019, p. 34). For example, in the EPD-report for a glued solid timber, a metric cube of their product had assumedly thermal recycling potential efficiency of 35 % in a bio-mass power plant. The presented values presented in Table 2-6 are assumed to substitute fuels from fossil sources. In similar way, steel products are shifting to rely on non-fossil fuel energy sources in their manufacturing.

Table 2-6 Re-used, recovery and recycling potential, relevant scenario details of a timber product. (Institute Construction and Environment, EPD, 2013, p. 5).

Description	Value	Unit
Electricity generated (per t atro waste wood)	1231	kWh
Waste heat utilized (per t atro waste wood)	2313	MJ

Justifying timber as ecological material based on carbon storages seems unfounded, because in the end of life cycle the stored carbon is released back into feedback system. Carbon neutrality is a term that has been widely used in the public, although the content of it varies a lot. It can be understood as zero fossil greenhouse gas emissions to atmosphere, or that the amount of released emissions is compensated by investing in projects that are mitigating GHG emissions elsewhere (Alhola et al. 2015).

From steel manufacturers point of view the environmental benefits are quantified based on reuse and recycling as stated in EN 15978 (2012). Benefits of reusable or recyclable materials are linked to a concept of circular economy. Circular economy refers to reusability of materials within a system boundary. If products can be reused or recycled without any loss in quality, those become valuable for future generations, see Figure 2-4. If products are disposed of as waste, they must be replaced by primary resources. reuse or recycling of materials and components also reduces the quantity of waste disposal. When planned and designed well, projects can achieve a basic level of sustainability with little to no additional cost. However, society in general does not prioritize the benefits of sustainable construction and does not understand the potential higher capital cost implications, thinking only of the initial cost. (Hauke et al. 2016, p. 4-6.)

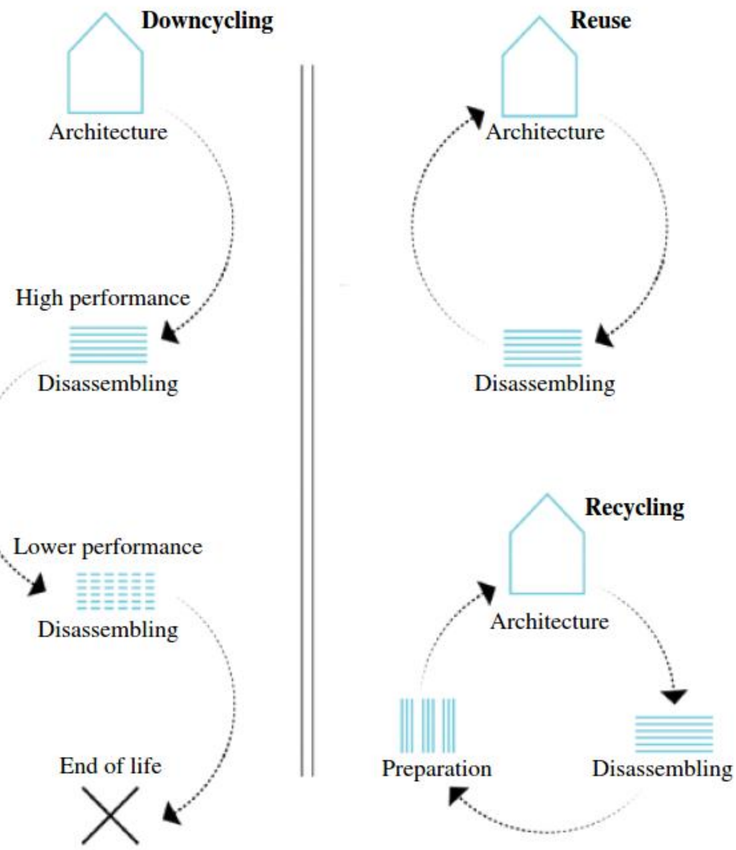

Figure 2-4 Downcycling, reuse and recycle (Hauke et al. 2016, p. 110).

Circular economy is an important concept when assessing the benefits of steel and wood products. In principle, all the structures should be designed to last long, allow modifications of purposes of space, to be easy to dismantle and to separate, the manufacturing should not create waste, instead side products can be used in secondary products. (Koskinen 2018, p. 1). Therefore, appropriate waste treatment or waste prevention are crucial and one of the displayed qualities in wood and especially in steel products. Whereas alternative scenario would be a linear economy, where the environmental impacts are ignored and production requires constant extraction of virgin resources, see Figure 2-5 (Sauve et al., 2015, p. 52).

Basic requirement 7 is new in the EU Construction Products Regulation: 'The construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the reuse or recyclability of the construction works, their construction materials and parts after demolition.'(Hauke et al. 2016, p. 22.)

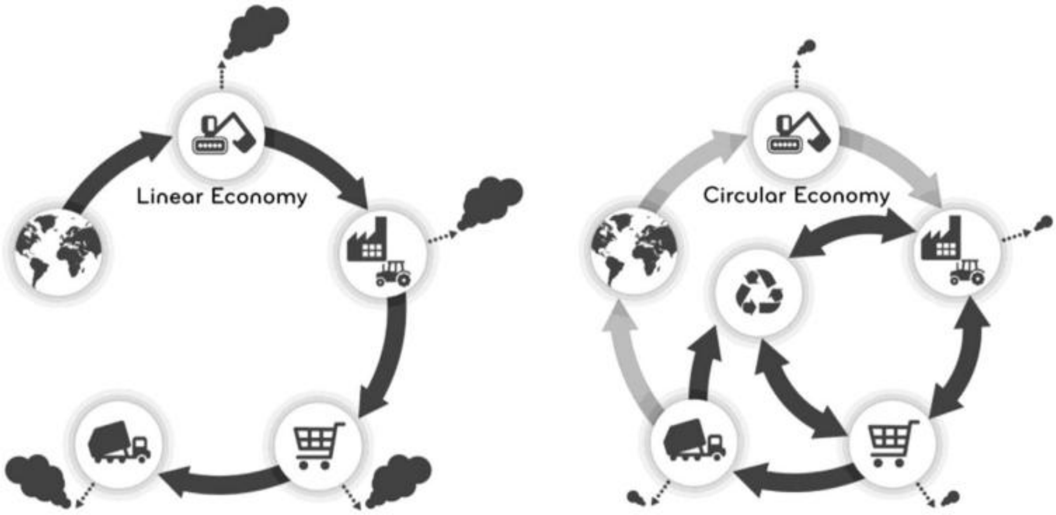

Figure 2-5 Visualization of linear economy and circular economy (Sauve et al., 2015, p. 52)

According to Oiva (2019, p. 25.) construction in Europe consumes more raw materials than any other industry. In Europe, most raw materials used in construction are non-renewable, where wood makes only 4 % of total annual raw materials. Even though in Finland wood makes 40 % of raw materials used on construction sites. In addition, construction and demolition of buildings generate about 40–50% of the amount of waste.

Koskinen (2018, p. 25) stated in his study, that waste treatment is currently questionable, 18 % of everyday waste comes from constructing or dismantling of buildings. In Finland, land transfer is considered as waste too, it being responsible of 73 % of wastes produced in Finland. Wood waste makes 6 % while metals make 2 %. 63 % of waste end up on landfill, while 35 % is burned at incineration facilities. If the wood is not incinerated properly, unfiltered harmful particles are released into the environment (Koskinen 2018, p. 45).

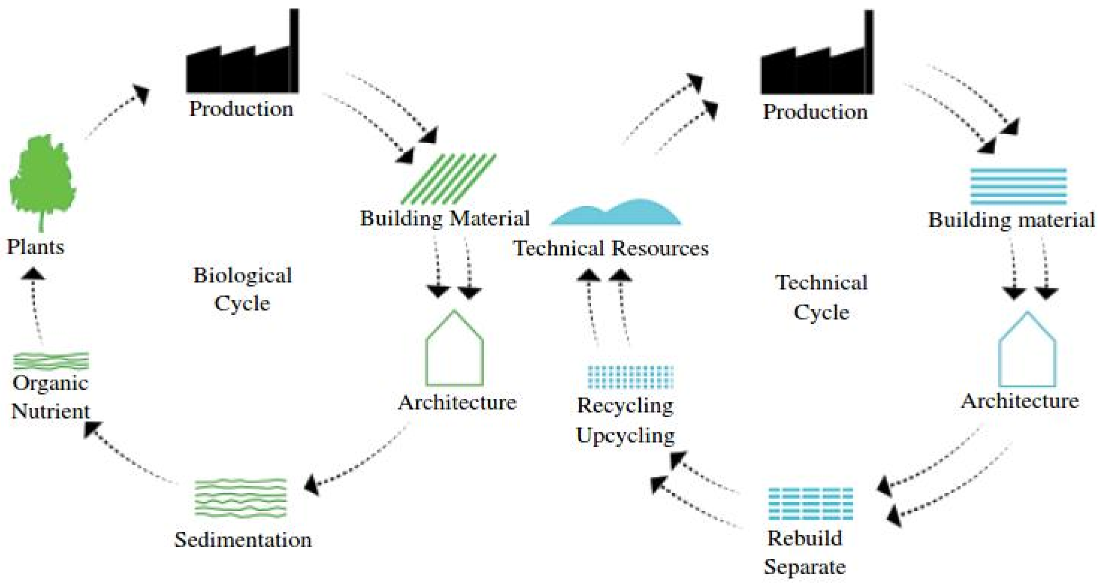

Figure 2-6 Biological and technical cycles ***(Hauke et al. 2016, p. 113).***

In a bigger scope, one can separate the recycling into two types. Wood belongs to biological cycle while steel to technical cycle as is shown in Figure 2-6. Steel can be upcycled to technical resource after it has been separated form building. Wood must go through sedimentation and growing before it can be used again as building material.

Varis (2019, p. 28-29) presented the idea of a circular economy as preserving of the resources and materials already produced in the economic cycle, even if they have reached the end of their service life for a certain purpose. According to the principle of a circular economy, products should be manufactured in such a way that they last as long as possible and, if necessary, are easily recyclable or recoverable. When the estimated service life of a building is reached, the material resources can be saved when the old members do not have to be completely replaced with a new one.

Reusing or recycling of material reduces the amount of wastes. 88 % of steel scrap is recycled and 11 % is reused (Hauke et al. 2016, p. 73). However, recycling of steel does not lose quality, but instead it replaces the need for raw material. The situation is somewhat different with those materials that can only be recycled on levels of lower quality: for example, when a timber beam is recycled for the first time it can be processed into boards (e.g. oriented strand board or OSB), in the next recycling step, it can be processed into a board of even less quality (e.g. medium density fiberboard or MDF), and finally there is only the possibility of processing the board into pellets and thus utilizing thermal recovery. (Hauke et al. 2016, p. 110).

In a study done by Virmavirta (2014, p. 28), the significance of recycling was evaluated from a material list of a single building. Each material was first evaluated as total emissions. Then reduction of emissions was based on how much can be gained from recycling, when building is needed to be demolished. In the third part the benefit of reusability was evaluated. Lastly the optimization was based on which option had the greatest savings, see Table 2-7

Table 2-7 The summary of all the GWP evaluations (Virmavirta 2014, p. 32).

Building material	Constructing kg CO_{2eq}	When recycled kg CO_{2eq}	When reused kg CO_{2eq}	Optimal result kg CO_{2eq}
Steel (& piles)	19 486	10 723	1 113	1 113
Concrete	11 636	10 181	11 636	10 181
Wall elements	12 977	6 553	0	0
Insulations (PU)	10 064	6 341	5 420	3 838
LCB	423	360	0	0
Wood	581	292	239	155
Windows	3 428	2 742	0	0
Gypsum	812	609	812	609
Steel sheets	1 301	701	1 301	701
Transportation	330	1 682	1 682	1 682
Total	61 036	40 184	22 203	18 279

The principle of a circular economy can also be applied to renovation, as the aim is to keep a valid building in working order for as long as possible. As the service life of a building is extended, material resources are saved when the old materials do not have to be completely replaced with a new one. (Varis 2019, p. 29). Varis presented a hierarchy pyramid for circular economy, see Figure 2-7.

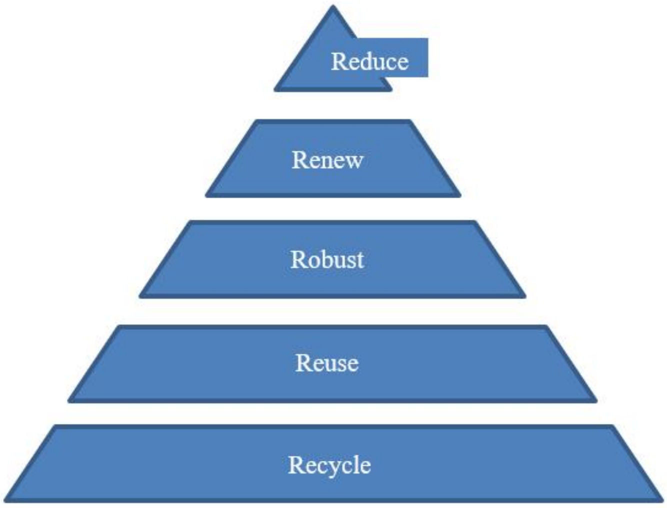

Figure 2-7 ***Principals of circulation economy. Recycle materials, reuse what you can, design robust structures, renew when needed and reduce consumption (Koskinen 2018, p. 24).***

Definition of handprint has disputes among researchers, some studies belittled it as a self-explanatory, while others would redefine or neglect it as seen suitable for their study. Disagreements among researchers can be seen in many written studies or reports. Nevertheless, when referring to the handprint term in LCA studies, a few misunderstandings may rise. One may argue that handprint is not captured at all in LCA. Others may say that handprint is already captured (Alvarenga et al. 2020, p. 1-2.) According to Ryhänen (2017, p. 9), rules for handprint are not clear and every study is more or less bias. Also, Viljakainen & Lahtela (2019, p. 14) stated that handprint has too much room for foul play.

2.5 Carbon emissions of buildings

Regardless if handprint is included or not, some studies focused on direct ways to lower carbon footprint, even if cutting down the emissions is not seen as a handprint. Especially when thinking LCA of a building, most of the emissions came from operational stage. In average, 33% of emissions coming from Finnish inhabitant comes from warming of houses (Varis 2019, p. 13). Energy efficiency of the building was one of the main focuses in achieving sustainability of society. Energy used for heating up building was responsible for 65 % of annual CO_{2eq} emissions in Finland. (Vuorinen 2020, TRY presentation). According to European Commission 42 % of energy consumption comes from building sector and buildings are responsible for 35 % of GWP emissions. (Hauke et al. 2016, p 13).

In an analysis done by Viljakainen & Lahtela (2019, p. 3) importance of energy source had the most significant effect on lowering the carbon footprint. Basically, the energy efficiency and the source of energy used for heating or electricity over the building's lifetime had the most significant share of total GWP value. Relevance of the structure came into play only when buildings used renewable energy during operation time, see Figure 2-8 and Figure 2-9

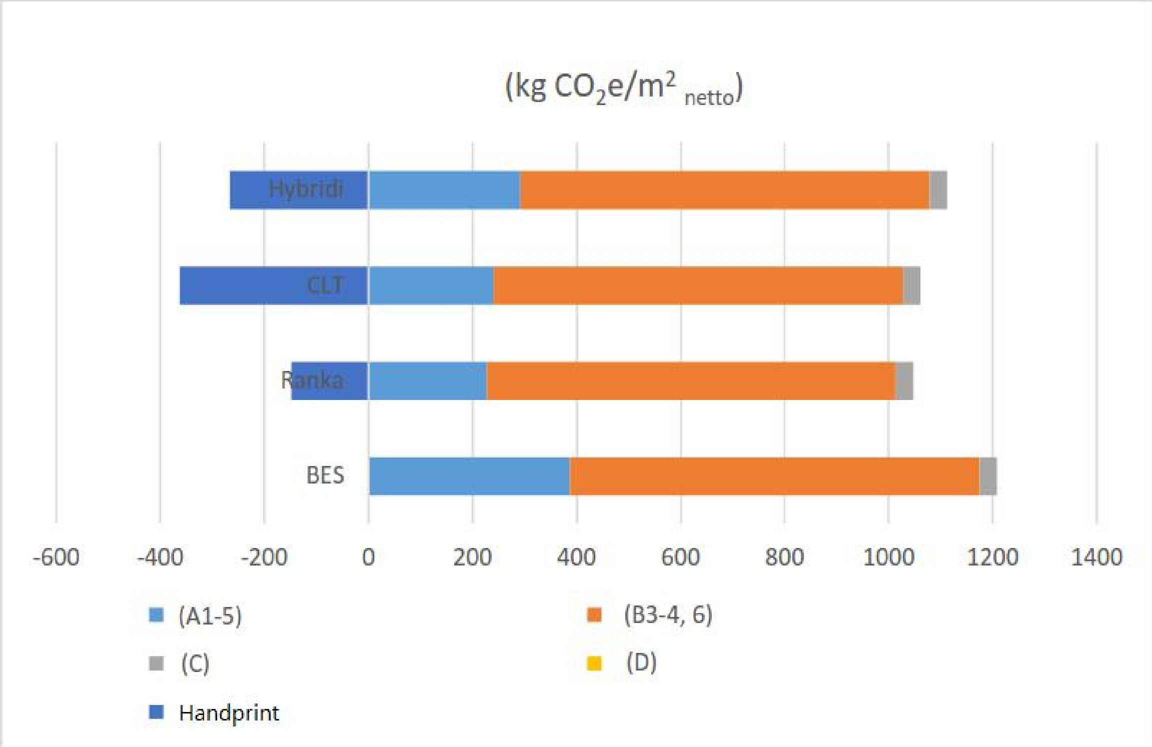

Figure 2-8 GWP emissions of each module A1-5, B3-4,6, C, D and carbon handprint. In this context Hybrid represents steel structure with wood envelope. Wood frame (Ranka) and Concrete frame (BES) with concrete envelope. The orange diagram is GWP coming from energy consumption during 75-years of operation time. (Viljakainen & Lahtela 2019, p. 14.)

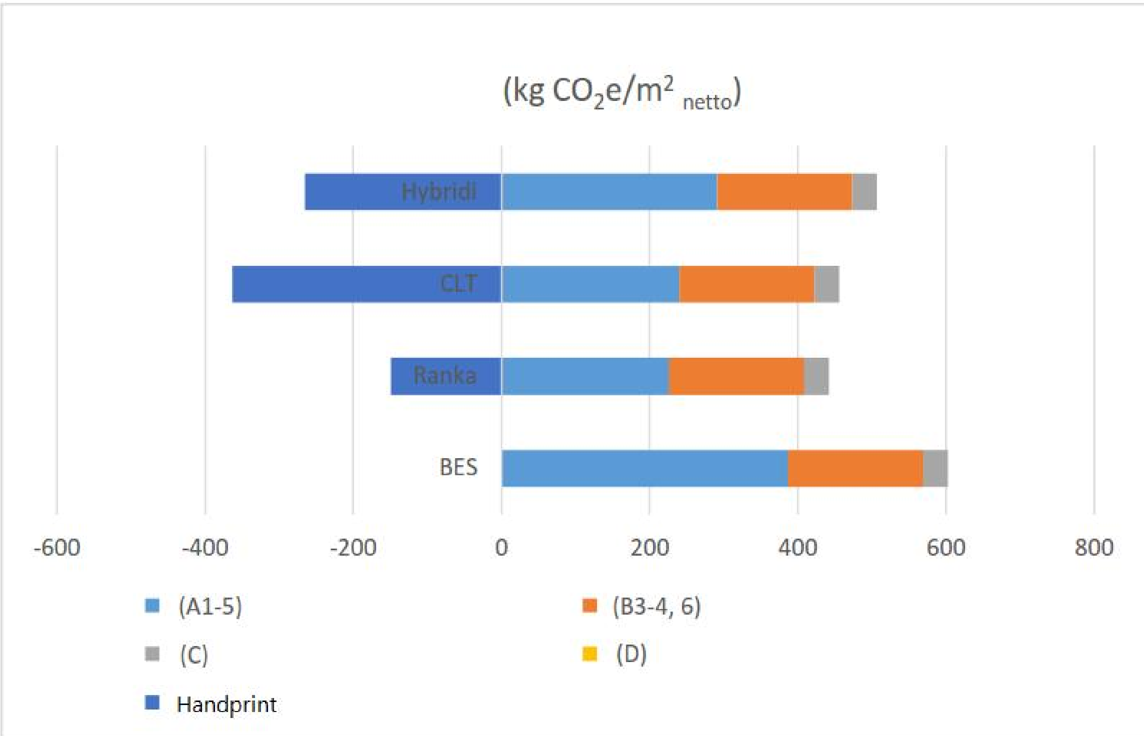

Figure 2-9 Porpotion of construction stage A1-A5 is greater when used renewable energy (Viljakainen & Lahtela 2019, p. 15).

(Viljakainen & Lahtela 2019, p. 14). The study included the carbon storages in the buildings structure and in the envelope. Especially for CLT-products the handprint was big enough to make up for the footprint coming from modules A and C. The operational time which is represented in module B however covers most of the emissions.

Even though the buildings in Viljakainen's & Lahtela's report are divided based on bearing material types which were hybrid (steel framed with wood envelope), CLT, timber framed with wood envelope, and concrete framed with concrete envelope, the buildings were depended on every material type. A visualization of relative proportion of GWP source coming from each material quantities is presented in Figure 2-10.

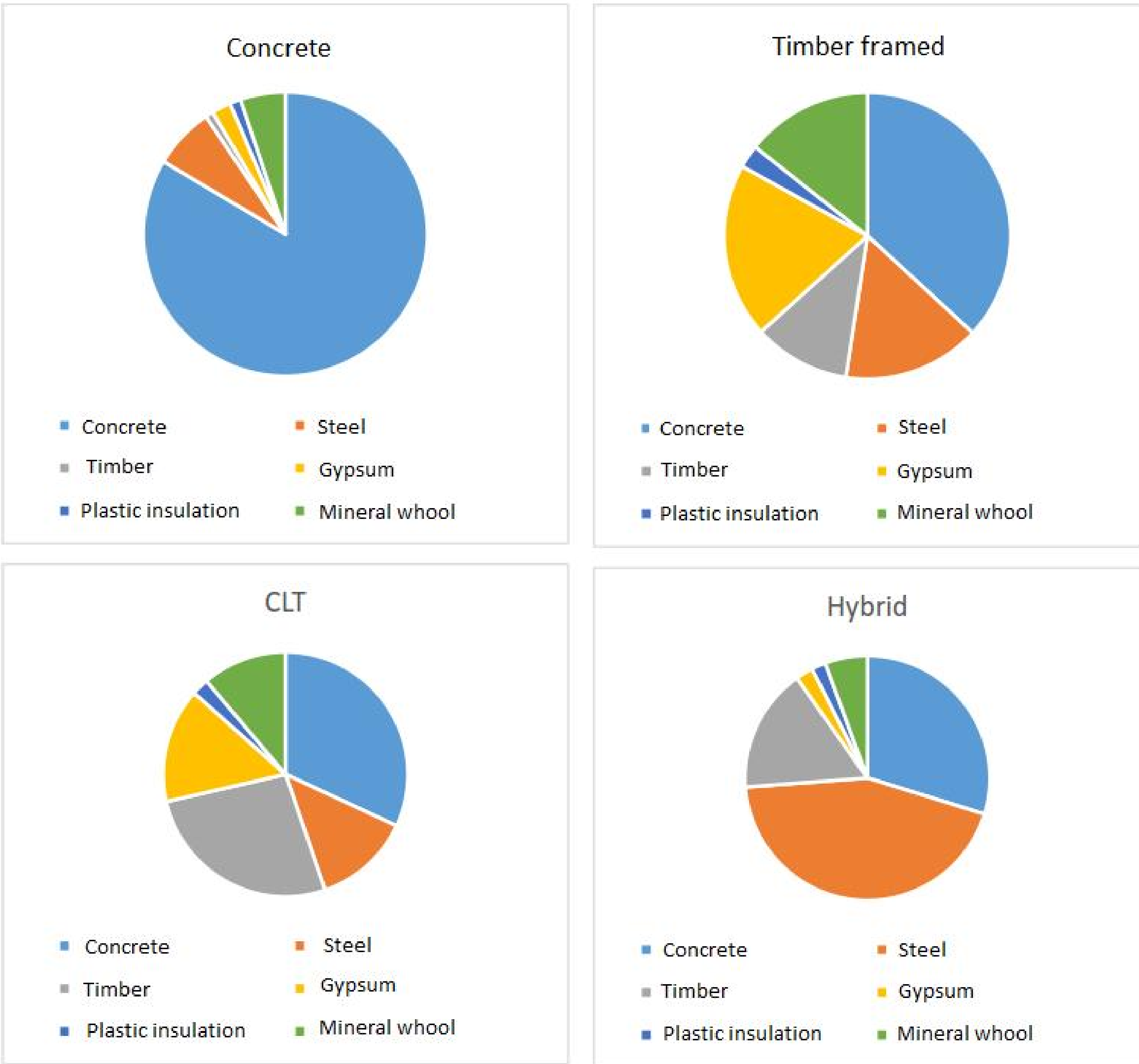

Figure 2-10 Portion of GWP per emission source, concrete, Timber, CLT, and Hybrid which represents steel framed structure (Viljakainen & Lahtela 2019, p. 23).

In general, a building can be divided into its parts or components. Each part or structural type produces a certain amount of emission per defined quantity. The quantity can be defined as unit length in meters or as square meters. The sum of all the parts should sum to the embodied carbon of the building. If the quantities of each part types are known, then multiplying them with their emission factor, gives the total carbon footprint of each components.

This type of breakdown gives a good way to recognize where the most emissions come from. For example, in research done by Viljakainen & Lahtela (2019, p. 25) the concrete floors in the timber framed house contributed the most, see Figure 2-10.

In a study done by (Lahdensivu 2019, p. 10), units were presented as kg CO_{2eq} per square meter. Each envelope or floor type was evaluated separately to distinguish contribution of each structure type, see Table 2-8. Once the quantity for each structure type was calculated, the total emissions can be determined by multiplying the quantity of structure types with their GWP factor. The results shown how much emissions per square meter are generated from each type of structure. Similar method was used in the study of (Liljeqvist 2018, p. 22.).

Table 2-8 Quantities are given as square meters. Each building type has exact information of material masses and emission factor. Table from (Lahdensivu 2019, p. 10).

	3rd floor	Entire building
Structure type	[m^2]	[m^2]
Non-bearing outer wall type 1	147	928
Bearing outer wall type 1	76	455
Bearing outer wall type 2	0	200
Outer wall shelter	0	195
Partition wall type 1	314	2 243
Shelter wall	0	113
Partition wall type 2	86	603
Intermediate floor type 1	512	3 814
Intermediate floor type 3	0	255
Intermediate floor type 4	54	428
Intermediate floor type 6	0	56
Base floor type 1	0	264
Base floor type 2	0	48
Base floor type 3	0	255
Upper floor type 1	0	510
Upper floor type 3	0	56
Balcony slab	29	200
Balcony fence	19	130

Ryhänen (2017, p. 27) noticed in his study, that the magnitude of emissions coming from envelope can be reduced by constructing multistory buildings. Thus, the foundations occupancy rate is higher, which results in better emission values. If CO_{2eq} is the main parameter, then the greater covered net area could reduce the relative emissions square meter. While in the other hand, the aim should be focused on achieving the necessary living space.

Cross-Laminated Timber (CLT) brings to market very capable product when competing especially with concrete technology. CLT products have life expectancy of 75 years on average and can be recycled or burned when they are dismantled. In comparison with equivalent concrete structure, the emissions were 23 % lower according to the study done by Oiva (2019, p. 26.) Whereas in another study, the differences of emissions coming from structures was 13 % at most (Viljakainen & Lahtela 2019, p. 14).

In some studies, comprehendible way to describe the total consumption of a building was done by comparing results to driving. A passenger car emits in average 160 g CO_2/km. Cars registered in Finland drove on an average 14 000 kilometers in the year 2017 (Lahtinen 2018). A construction of a concrete apartment in a study done by Liljeqvist (2018, p. 27-28) had equal embodied carbon as 300 cars driving for a year. While if concrete were replaced with wood, the construction of the building would have been equal to driving 217 cars in a year.

Even though, building from wood does not automatically mean that the building is more ecological. For example, if forestry is not done within the permitted limits, or manufacturing and drying of products consumes a lot of energy or if most of the material ends up on land fill. (Koskinen 2018, p. 11.) Weather the carbon sink and carbon storage are included or left out of the calculations, wood materials have relatively low GWP emissions. Lightweight structures should contribute further to lowering power requirement during transportation and installation. To achieve better ecological and efficient timber products, there is a need for more timber industries in Finland. In current state raw materials are sold abroad and final product is bought back in (Koskinen 2018, p. 66). Yet the initial costs according to Finnish study were 10 % higher when building from timber. During the lifetime, the price difference drops to 0-3 %, due to operation time expenses (Ryhänen 2017, p. 1). Whether the effort is worthwhile is up to the funder and the users.

Regarding the statistical certainty it should be mentioned, that to have a high reliability of accuracy, the sample size must be adequate. For an example, a study made of 22 buildings in Germany had a result of distribution of GWP between operational and construction phase to be divided as 30 % in construction and 70 % in operation stage (Schlegl et al. 2019, p. 346). This suggests that in average, the significance of reductions of carbon emissions in construction stage influence the 30 % of GWP emissions when comparing to the whole lifespan of the building, see Figure 2-11 and Figure 2-12.

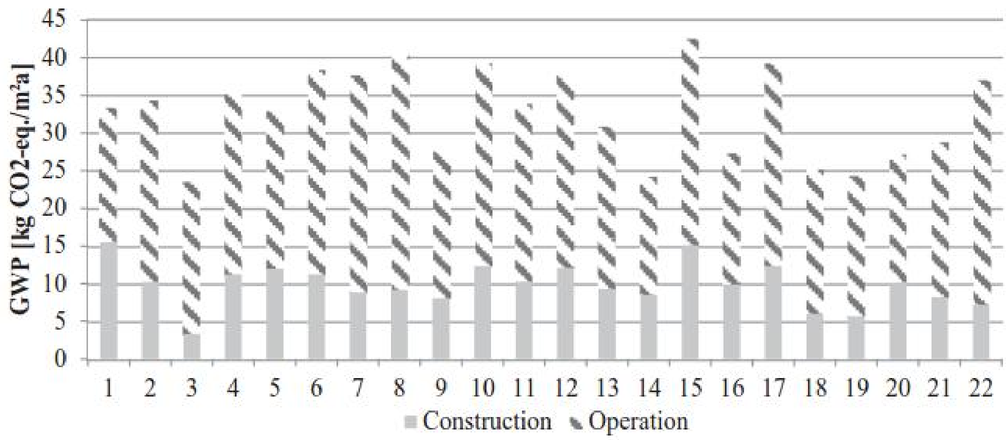

Figure 2-11 ***GWP of each building (Schlegl et al. 2019, p. 346).***

To determine the margin of error based in statistical methods, the certainty of the error range is defined as:

$$e = z_{0.95} * \sqrt{\frac{p(1-p)}{n}}, \tag{1}$$

Where	e	estimated margin of error
	$z_{0.95}$	critical value associated with the level of confidence
	p	Relative frequency calculated from the sample
	n	sample size

If the confidence is set to 95 %, that means that value for two-time standard deviation is 1.96. The value p is assumed to be 70 % based on the sample size of 22 buildings. Then the estimated margin of error can be calculated as:

$$1.96 * \sqrt{\frac{0.7 * (1-0.7)}{22}} = 0.191\,, \tag{2}$$

Therefore, for 22 buildings, the confidential range is between ± 19.1 %. If equation is reversed to determine the sample size so the margin of error is reduced to 5 %, then the sample size has to be at least 332:

$$1.96^2 * \frac{0.7 * 0.3}{0.05} = 332\,, \tag{3}$$

Statistically 22 buildings do not give reliable certainty for true distribution of emissions. But it does help to notice the most probable factors. The variation of each part, the construction and operation are visualized in Figure 2-12. The figure is a common way of showing the boundaries of the results with 50 % of the results belonging within the boxes.

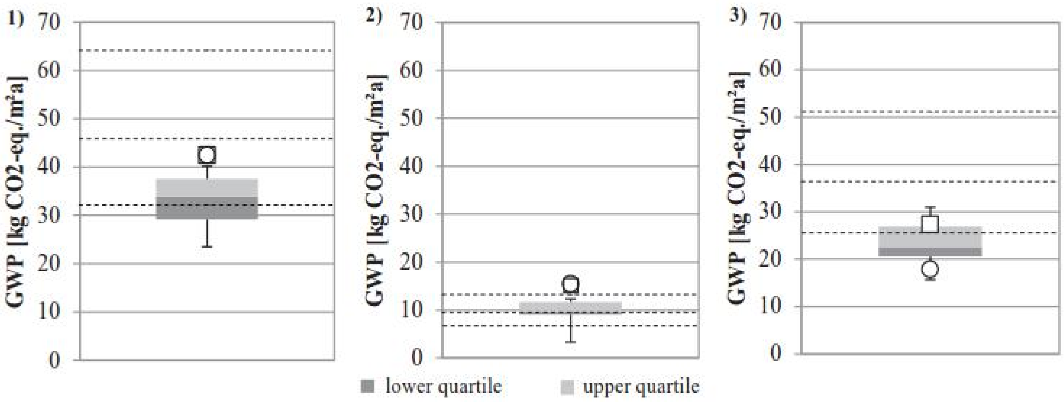

Figure 2-12 Variances of GWP from 22 buildings, on the left the variation of total emissions, on the middle the variation of construction emissions and on the right variation of emissions from operations. (Schlegl et al. 2019, p. 346).

Most studies reviewed in this thesis focused either on a single product or a single building. However, to make reliable claims of the evidence that are available, the sample sizes need to be bigger. Therefore, any evidence that is used to warrant a claim has a risk of being misleading or at worse case wrong. Secondly the sample size does not necessarily mean that the evidence is reliable, also the methods used to determine the embodied carbon have a risk of lacking the validity, which means what does the method measure. For example, when assessing embodied carbon, there is a possibility of missing a significant proportion of emissions doe to a systematic error or due to unprecise measuring tool.

2.6 Carbon emission of steel structures

Steel is almost essential for the society as a building material, and its demand has been constantly growing. However, greenhouse gas emissions from steel are remarkably high, with steel production accounting for 7-9% of global CO_2 emissions. (Varis 2019, p. 23.) Most significant part of steel's emissions comes from extraction of iron ore and from refining it into steel in a blast furnace (BF). Heating in BF is done by burning coke which further increases the release of carbon emissions in the process. However, emissions from blast furnace-based steel production can be reduced by improving material and energy efficiency in the production processes (SSAB 2019 report, p. 52). Byproducts such as fly ash when using BF are caught and utilized in other products. Furthermore, once a product is recycled as a scrap steel it can be melted without excessive use of energy as done when refining the virgin material. In Northern countries the proportion of reused steel scrap makes 20 % of raw materials (SSAB 2019 report, p. 51).

Alternatively, the processing of steel scrap can be done with an electric arc furnace (EAF), where recycled steel can be melted and refined in more efficient way. Furthermore, EAF has the possibility to use 100 % fossil free energy. Energy requirements for EAF are yet tremendous, requiring 10-12 terawatts in a year, which is equal to one full nuclear power plant. (Varis 2019, p. 24). Given today's price of electricity, cost of fossil-free steel would be 20-30% more expensive.

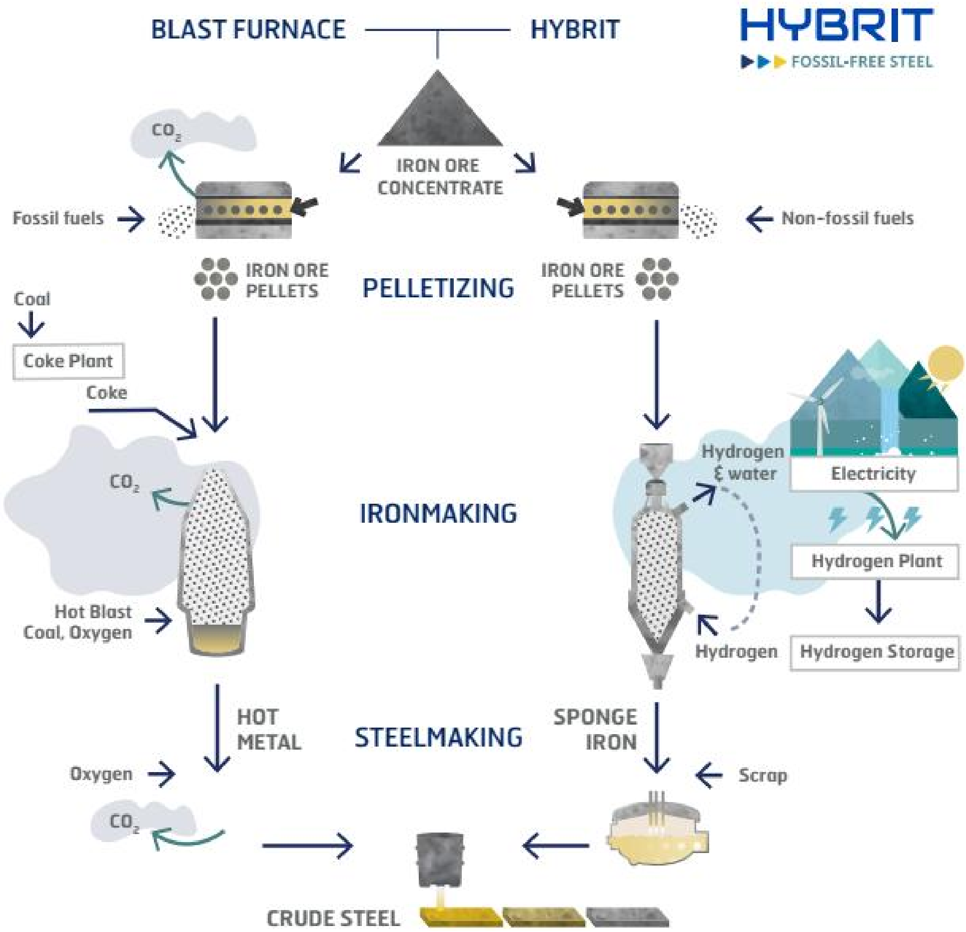

Figure 2-13 ***SSAB is aiming to replace blast furnaces with a HYBRID furnace, which utilizes hydrogen technique in ironmaking.***

Nevertheless, industries in Nordic countries aims to bring fossil-free steel into markets by 2026. Currently recycled scrap will not sufficiently meet the growing demand for the steel. (SSAB 2019 report, p. 27). To enable the use of recycled steel scrap and to improve the energy efficiency in manufacturing, Nordic countries have been preparing for hybrid furnaces, see Figure 2-13. Steel is a unique material that retains its properties no matter how many times it is recycled. Using recycled steel scrap in production increases material efficiency and further reduces CO_2 emissions (SSAB 2019 report, p. 54).

When considering sustainability in construction, steel structures and steel components often meet this requirement. Steel proves to be especially effective with higher load cases, see Figure 2-14. Using long-span construction with open column-free areas and relatively small cross sections, steel structures are extremely economical, resource efficient and flexible. Steel buildings are capable of being adapted economically to another use, and so natural resources are used sustainably. (Hauke et al. 2016, p. 22.)

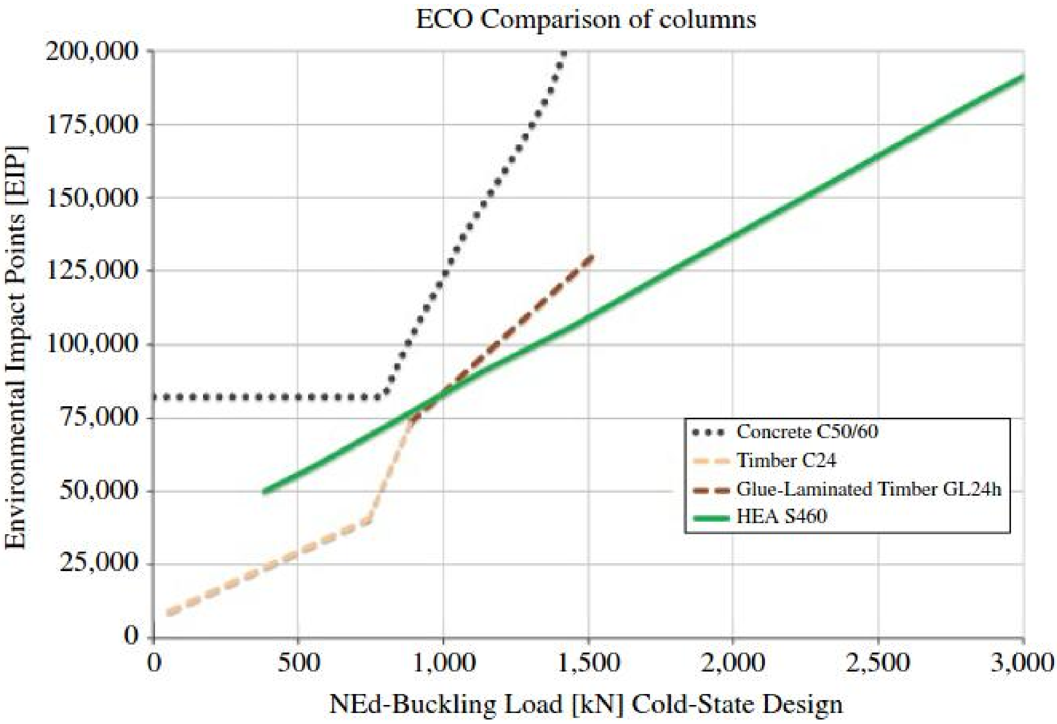

Figure 2-14 When load carrying capacity is critical, steel columns performs better after exceeding 1000 kN. (Haule et al. 2016, p. 92.)

Structures with steel frames are normally considered as an economic option when the designers require longer spans for large open spaces, for example, in industrial buildings, large retail areas or open offices. (Hauke et al, 2016 p. 53). Steel should be designed as sparse material and spend effectively. Especially if aiming in lowering of embodied carbon in structures, the frames require appropriate optimization in design. On the other hand, high utilization ratio limits the buildings modifiability in the future.

Haapio (2012) presented a feature-based costing method for evaluation of steel structures, which combined different sources of expenses from energy requirements, wear of tools, materials, transportation, and installation of the product. The method was later applied for assessing the GWP of steel products, where emissions coming from every feature of the designed product were counted (Haapio et al. 2013, Heinosuo et al. 2012)
In Haapio's research, focus was to determine how the stiffness of a steel connections affected the price of the beam. According to his study, the pinned joint solution was 24 % and the fixed joint solution 16 % more expensive than the semi-rigid solution. (Haapio 2012, p. 82). When comparing the GWP of each connection type, the semi-rigid connection had lower emissions than the other two options, the reduction was about 6 % from total emissions.

Haapio's framework included cradle to gate modules A1-A3 with the addition of modules A4 and A5 for transportation and installation time of beams. The fastening time of connections defined the usage requirement of a crane, a forklift and a manlift, which were responsible for 13 % of the total GWP emissions. Therefore, lowering installation time helped reducing the total emissions. Other important sources of emissions came from bolts and welding wire which are normally neglected in LCA (Haapio et al. 2013, p. 14-15).

Beside design aspects, an engineer has a variety of options when choosing the profile type and manufacturing method of the steel members. Profile types influence the bending stiffens of the member while material choice determines the strength. Manufacturing method typically determines the precision of dimensions of a product, where cold-formed members have usually smaller deviations compared to hot rolled products.

Steel manufacturers have been promoting high strength steel as lighter option compared to normal strength steel, see Figure 2-15 (Hauke et al. 2016, p. 294.) Lowering of buildings total weight reduces transportation requirements, thus further lowering the total costs and carbon emissions (SSAB 2019-report, p. 56.)

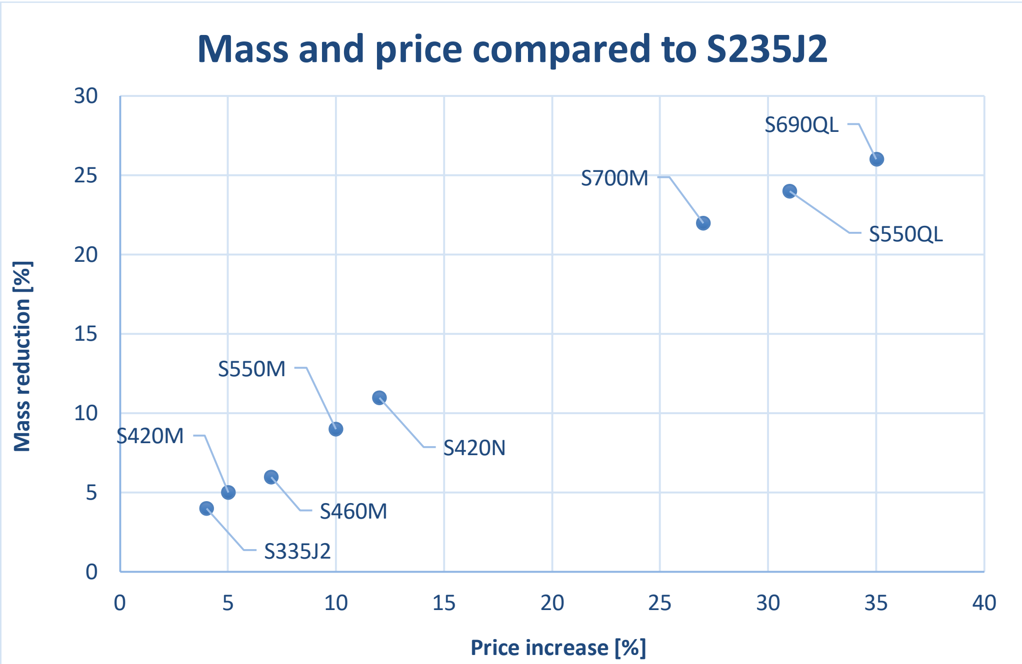

Figure 2-15 ***Relative increase of steel price and mass reduction compared to S235. (Hauke et al. 2016, p. 318.)***

In Nordic countries, most typical steel material is S335J2 which is used in hot rolled profiles. Whereas S420N can be used for cold formed profiles. Closed profiles can be made by both materials and both methods, whereas open profiles are made of S335J2 and by hot rolling method.

In a study presented by Johnson et al. (2017), comparison of hot-rolled and cold formed steels of 18, 24 and 30 m spans had differences in costs Figure 2-16 and in GWP emissions Figure 2-17. The results indicated, that of hot-rolled steel (HRS) required more labor in installing of the frame, whereas labor and crane hiring costs in cold-formed steel (CFS) portal frame were 14% cheaper. For the 18 m span building, the cold-formed steel frame required 33% less steel, therefore the overall building was 33% cheaper, primarily due to the reduced crane hiring cost (Johnson et al. 2017, p. 84).

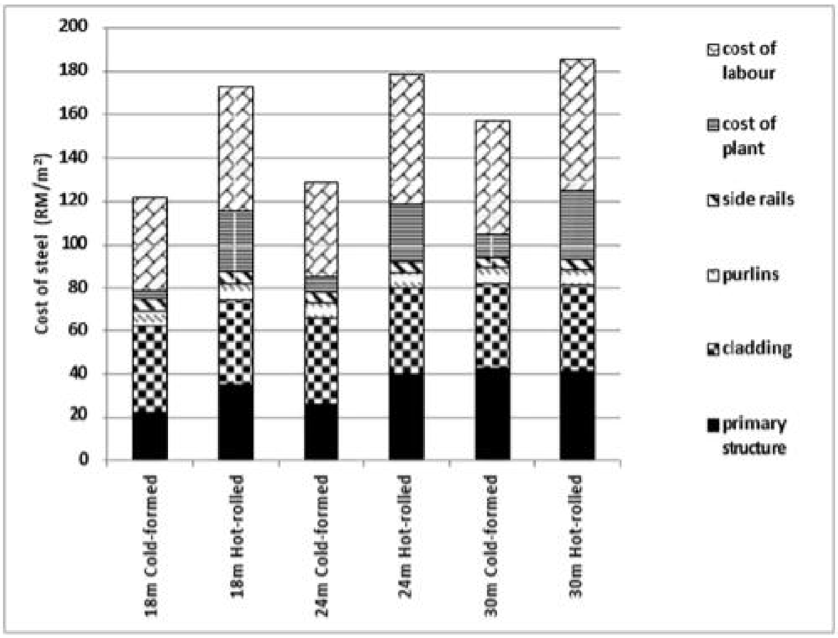

Figure 2-16 Life cycle cost of frames (Johnson et al. 2017, p. 85)

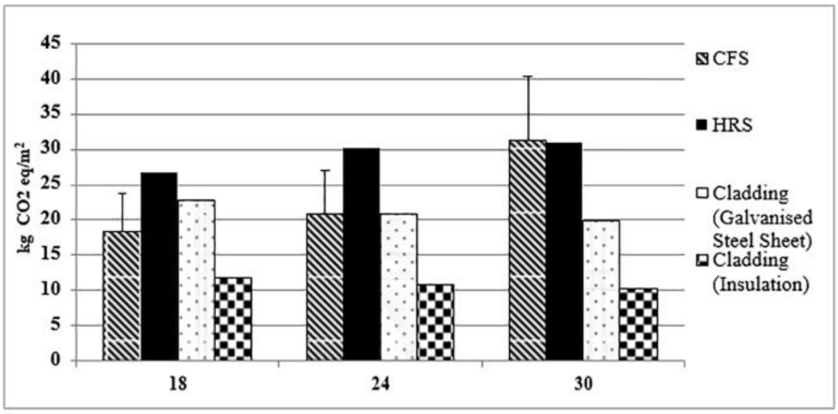

Figure 2-17 Embodied carbon of primary structure and cladding per m^2 (Johnson et al. 2017, p. 84).

Presumably, the slender structures that can be achieved with design of steel trusses are particularly prominent at longer spans. Open profiles can be used in the design of smaller halls, where standardized profiles can be used as a single beam. High space efficiency is fundamental when aiming in sustainable construction. Improving space efficiency means to meet floor area needs without compromising or even increasing land use. (Hauke et al. 2016, p. 102).

To determine the total GWP of a certain structure, the GWP emissions should be studied as a sum of its components. LCA must consider EPD's for the products and operations which are used in transportation and assembling. When comparing the results between buildings of different size, the GWP need to be divided by net area and design life of the building. This type of unit makes the results comparable among different buildings. Furthermore, handprint of the steel should be based on the circular economy. Steel can also be considered as a safe material for environment based on other indicators in EPD reports.

2.7 Methodology in assessment of GWP

There are many LCA tools that have collected data for evaluating sustainability of the buildings. The method of calculation in LCA tools is based on different schemes coming from organizations such as BREEAM, LEED, DGNB or currently viable guide for low carbon assessment from the Ministry of the Environment. Often the assessments are based on the masses of the materials. Each material needs to be defined as some part of structure, to have a realistic factor for estimating additional emissions. Assessment guides from the Ministry of the Environment allows to use different tools for assessment of buildings. Note that assessments carried out using different emission data or tools do not ensure comparability (Kuittuinen, 2019, p. 13.)

Sense 2009, a German online database ÖKOBAUDAT has been available to anyone interested in evaluating ecological impacts of the buildings. (Hauke et al. 2016, p. 66). Database uses information that has been gathered globally. Some information of materials is based on average values that have been available. A concern raised in reliability of data when comparison was made between the database and European EPD's of steel products. The GWP-values were -49 % to -71 % according to EPD's, see Figure 2-1.

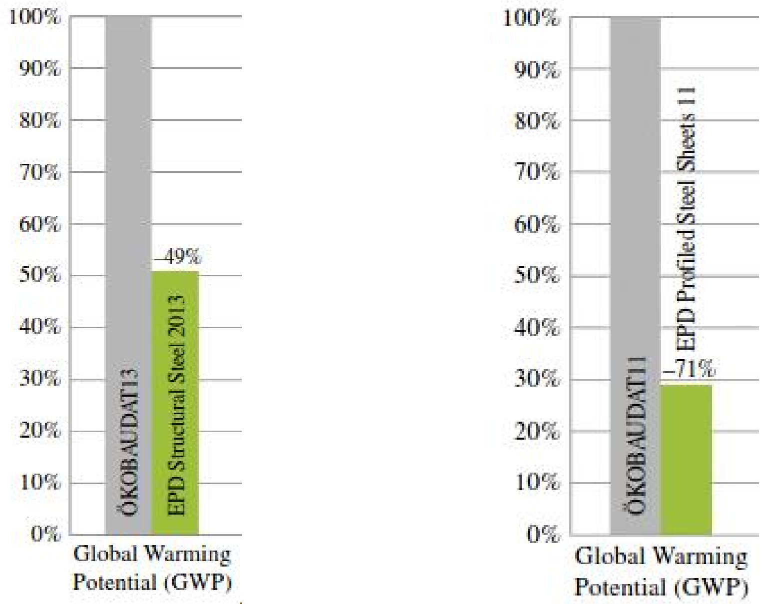

Figure 2-18 GWP comparison between ÖKOBAUDAT data and EPD-report. (Hauke et al. 2016, p. 79).

Even though ÖKOBAUDAT has its uncertainty's, other database tools have been made based on LCA method. The well-established programs include the GaBi, ThinkStep and SimaPro software. All the programs can access many different background databases and are not only suitable for preparing LCAs but enable the user to simulate different scenarios and thus strive to achieve optimization (Hauke et al. 2016, p. 65).

In a study compare LCA software GaBi with SimaPro, was carried out by assessing two buildings of different types. Software's had many substances they evaluated, but there was no clear synergy found between the results, as it is shown in Figure 2-19. Besides, variation of results on fossil depletion from two buildings resulted in 9 to 42 % and on climate change from -16 % to 13 %. The results indicate that the two assessment tools return mostly completely different estimates at the level of the whole building (Emami et al. 2019, p. 15).

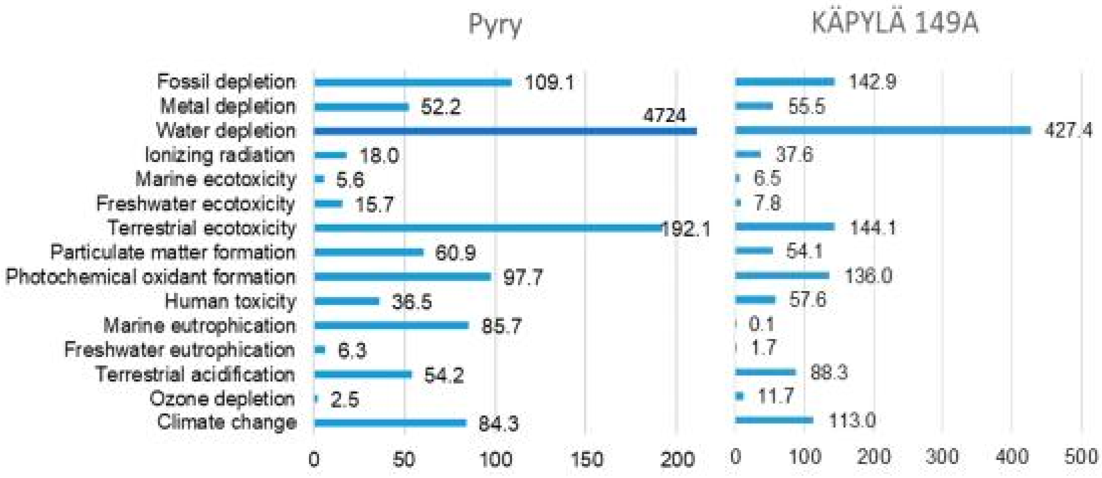

Figure 2-19 Comparison of two buildings (Pyry a detached house and Käpylä an apartment house) where SimaPro is set to 100 and variance of each category is presented in the charts (Emami 2019, p. 9).

Even though both software's had similar schemes, and both used LCA for their calculation method, the results were very different. Study used only two different type of buildings that were evaluated, for statistical certainty more buildings are needed for better confidence. Having such a different result should still in any case questions the estimated quantities comparing the superiority between products.

Lahdensivu (2019) conducted a study of emission evaluation using online software's such as One Click LCA, which uses material masses of a building to evaluate the total emissions. In her study emissions were calculated using the areas of each building type. Calculation based on materials of a structure type resulted in 25 % smaller emissions. Where One Click LCA gave 1231 tons of CO_{2eq} while manual calculation gave only 906 CO_{2eq} (Lahdensivu 2019, p. 14).

2.8 Methodology in this thesis

Assessment of embodied carbon in this thesis will be carried out by manual work, where GWP of products is determined with EPD reports and other accessible databases such as Lipasto unit emissions (Lipasto, 2017). The manual handling of inputs offers an opportunity to adjust how the results are calculated. As the module B represents the operational stage, structures do not contribute to emissions, unless repair or replacement is required during its life cycle.

Thesis will use Cradle to Grave EPD's with the optional C module. Modules B1-B7 will be excluded, as they are related to operational stages. Wood materials are designed for same design life as steel. Comparison of steel frames will be following Haapio's (2012) method with modules A1-A3 to determine GWP of products and the modules A4-A5 to include the impact of design. The total weight of structures will be used to determine the GWP of transportation and lifting when using cranes or manlifts. For wood products, the GWP is counted from A1-A3 and C1-C4 to include the release of biogenic carbon. Module D will include saved GWP coming from recycling of materials and energy production in incineration facility.

Beside main bearing members of the structure, this thesis will include the quantity of connecting and fastening parts. Reason is to have as realistic and accurate embodied carbon of the total structure. Therefore, the assessment will include GWP of bolts, anchoring bolts, reinforcement of members, connection plates, weld material, welding gas, concrete in footing, reinforcement in footing and horizontal bracings.

Since boundary conditions of a steel beam affected the required beam size, then considering the static model of the entire frame should influence embodied carbon emissions. In Haapio's study (2015) semi-rigid connections reduced the total price of the beams. Connection types either directly lowered GWP compared to other connections, or they reduced the material requirement of the beam. However, designing semi-rigid connections is an iterative process, adding cost to the design phase. Benefits from material savings must outweigh design costs.

Design of frames should consider available products and use the option with the lowest GWP. Cold formed steel is supposed to reduces the weight compared to hot-rolled steel. High strength steel should further help reduce the total weight of the frame, even if it requires more energy in manufacturing.

The competitiveness of the steel structure in terms of carbon emissions compared to wood structure is interesting, as several studies avoided a direct comparison. Wood and steel have typically different design life, waste disposal and recycling, precision of manufacturing and design requirements. Comparison of the GWP emissions will be divided by square meters, so the comparison becomes comparable with buildings of different sizes.

3 GWP analysis of the frames

This chapter presents types of frames, members and connections used to determining the embodied carbon of each structure. The aim is to see how different solutions in frame types contribute to the total GWP. Compared frames have different boundary conditions and members have different properties. The properties are based on the assumptions that cold-formed high strength steel lowers the GWP emissions. The frames are compared with different span lengths of 10 m, 15 m, 20 m, and 25 m to produce more reliable results.

According to Johnston et. al. (2017, p. 82) the cold-formed steel frames were lighter than the hot-rolled steel frames for both 18 m and 24 m spans but not for 30 m spans. In this study the hot rolled members were open profiles while cold-formed members were tubular. Cold-formed steel profiles were either rectangular tubes (RHS) or square tubes (SHS) Figure 3-1, tube profiles were made of higher strength of S420MH. Open profiles IPE, HEA and HEB Figure 3-1 were made of normal steel strength S355J2.

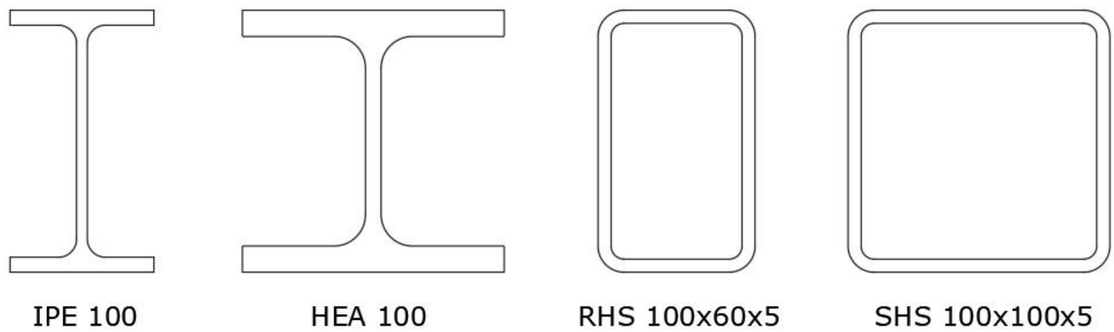

Figure 3-1 Open profiles I and H on the left, rectangular and square closed profiles on the right. Dimensions for 100 mm high profiles are standardized, meaning that other dimensions are either fixed or limited.

In this chapter, the studied assumptions in steel frames are as follows:

1. Semi-rigid beam to column connections reduce weight of beam compared to rigid or pinned configurations.
2. Higher steel strength reduces weight of the frame.

This analysis goes through the procedures that are required when designing a low carbon steel structure. Analysis is aimed to verify that the claims mentioned above truly work, and if anomality's are found trying to identify what could possibly cause it. Having multiple frames of different spans helps to recognize if design boundaries have correlation with the lowering of the total GWP emissions. Lastly steel frames in general will be compared to wooden frames. According to literature, these claims should also be found true:

3. Wooden frames have smaller carbon footprint than steel frames.
4. Wooden frames have steeper growth of emissions compared to steel when span length increases gradually.

As modules A4 and A5 are required in building's life-cycle information, their significance will be compared to modules A1-A3 and C1-C4.

5. Transportation and installation time are significant part of total GWP.
6. Connection plates, bolts and anchors and welds are negligible when estimating total GWP.

New regulations exclude connecting parts in preliminary assessment. However, most materials require steel connectors or reinforcements. Excluding these parts might remove relatively significant part of embodied carbon from assessment. Therefore, connection plates, bolts, anchors, reinforcing rods, and are included in this analysis. Even though regulations from the Ministry of the Environment allows leaving them out from evaluations.

This study compares different static models in each span length. The aim is to compare how design requirements influence the embodied carbon. The material emissions are summed form cradle to grave modules A1-3 and C1-4. Module A4 is included to demonstrate the importance of transportation and the weight of the structure. Whereas module A5 highlights the importance of installation time at construction site.

Module D is included for the parts related to reuse and recycling. In this analysis the module represents potential reduction of carbon emissions in the circular economy. Steel material replaces virgin materials and wood replacing fossil fuels in energy production.

3.1 Loading and deflection restrictions

The study limited the frames to have a controlled number of variables between the frames. Frames were made of different materials and member types. Whereas loading and dimensions were same for every case of similar span length. Loading was not increased and spacing between frames was 6 m. Self-load was included but permanent load from envelope or roof was neglected in this analysis. The vertical load was formed by snow load, and horizontal load consisted of wind load.

Snow and wind load were used as testing loads in this study; therefore, this study did not consider the irregular distribution of snow load as it is required for snow loads in the EN 1991-1-4. However, combination of loading was based on EN 1990-1-1, where combination factors for snow and wind loads were applied for ultimate limit state (ULS) and service limit state (SLS). Design requirements was verified according to Eurocode. Snow load was evenly distributed trapeze load in every case.

- Spacing between frames 6 m.
- The snow load was set to 2.5 kN/m^2 area load, or 15 kN/m line-load.
- Snow applied as a trapeze load.
- Open profile beams were loaded from the top surface ($z_g \neq 0$ mm).
- The wind load was according to EN 1991-1-4, with d/b ratio equal to 4.
- Columns were loaded with wind load factors D and E.
- The deflection for beam is limited to L/300. (from Finnish NA)
- Deflection of columns were limited to L/150. (from Finnish NA)
- Lateral restraints every 5 m connected to the top chord or the side of the beam.

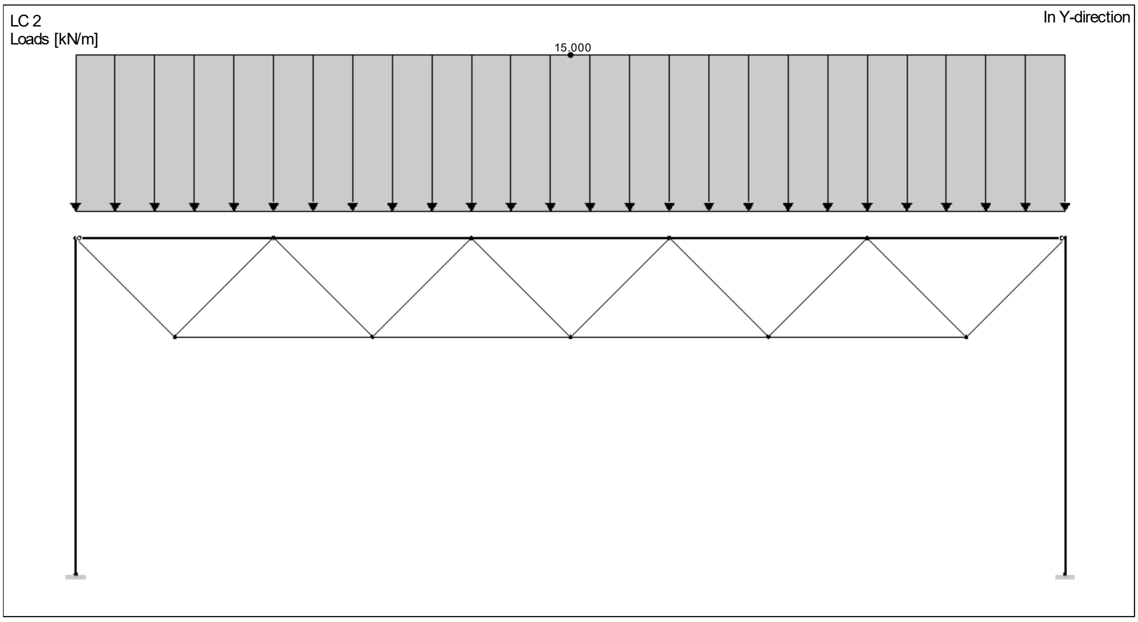

Figure 3-2 Applied snow load 15 kN/m

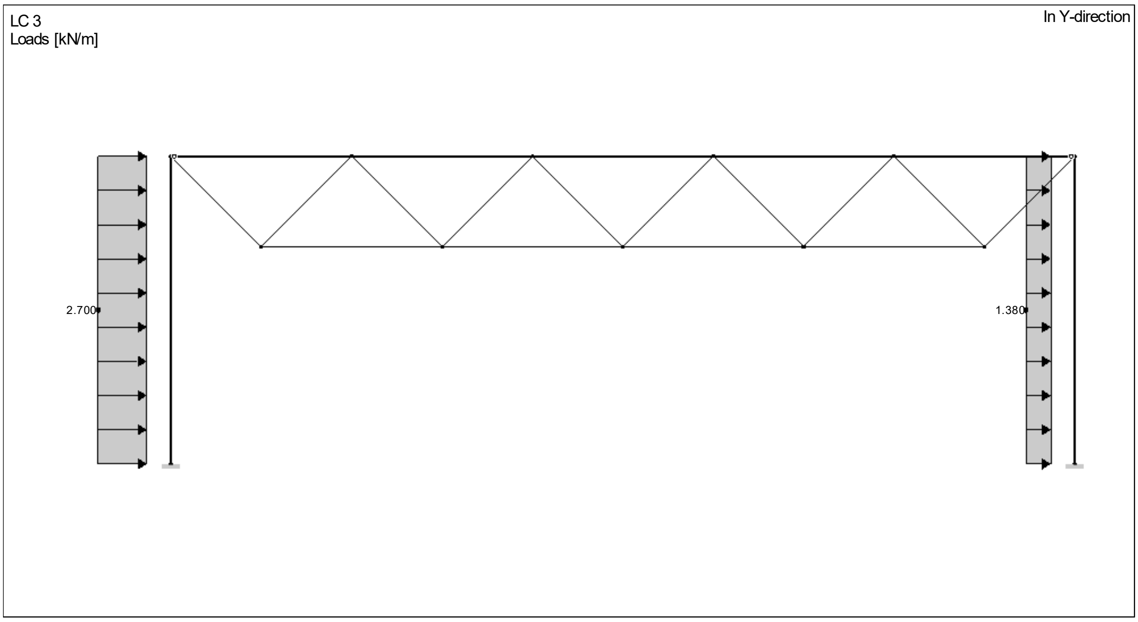

Figure 3-3 Applied wind load to the columns according to Eurocodes. Overpressure and under pressure considered. Values based on the max height of the column and width of the span length with d/b ratio equal to 4 (EN 1991-1-4).

3.2 The procedure of designing steel trusses

This analysis forms in total of 25 frames, from which 8 were steel trusses with a span length of 20 m and 25 m. The geometry of each frame type is found in appendix C. The trusses were made of rectangular cold-formed steel with the material strength of 420 MN/mm^2. The trusses had either fixed or pinned boundary conditions. If a truss had a fixed connection to the column, then the base connection of the column was pinned, see Figure 3-4.

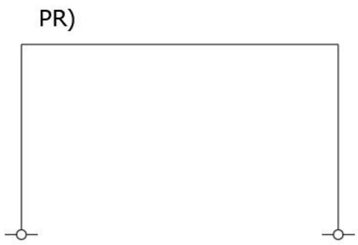

Figure 3-4 PR) rigid frame with pinned connection in the base. RP) pinned frame with fixed base connections.

Top chords are connected to the column with a seated connection. A single connection to the column is assumed to be a pinned connection. For the frames which classify as rigid, the bottom chord of a truss must be connected directly to the column. Pinned frame configuration requires, that the bottom chord does not have separate connection to the column, see Figure 3-5. Truss design is based on recommendations found in structural tubes manual (SSAB Domex tube, 2016). Trusses are designed to have the constant height of L/10, see Figure 3-6, while the double tapered trusses had the maximum height of L/10 in the middle and a height of L/20 in both end, see Figure 3-5. Double tapered trusses were added to the comparison due to the fact, that wooden beams in longer spans are typically double tapered, see chapter 3.5 Design of wooden frames.

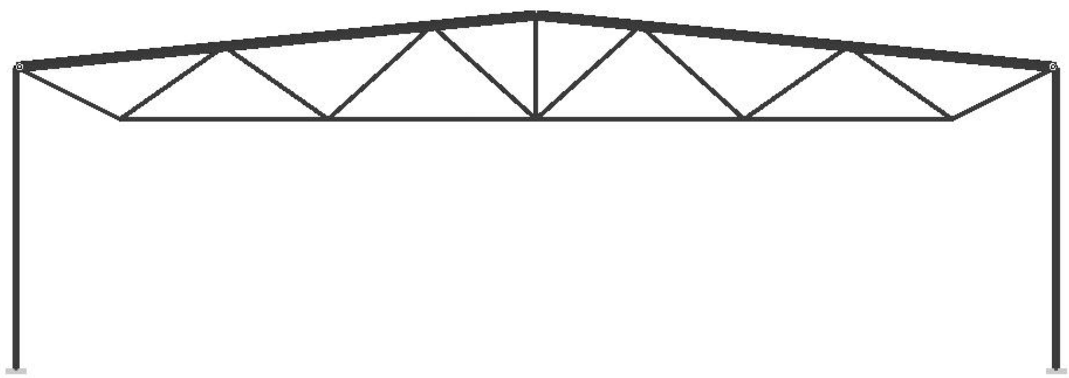

Figure 3-5 Double-tapered truss with pinned connection to the column.

Design models were made in FEM program Dubal RFEM 5.20. The program calculated every load case for each member and checks them for Eurocode requirements.
Figure 3-7 shows the distribution of normal forces in a frame. The top chord in a truss is always in compression, and therefore must be checked for the buckling. The bottom chord

in case where it is not connected separately to the column, is entirely in tension. The parts that are only in tension are designed as:

$$f_{yd} \geq \sigma, \tag{4}$$

Where	f_{yd}	Yield strength of the steel
	σ	Calculated tensile stress in the member

$$\sigma = \frac{N_{Ed}}{A}, \tag{5}$$

Where	N_{Ed}	The applied axial force in the member
	A	Cross-section's area of the member

The lateral movement was restrained with bracings, which are connected to the chord every 5 m, as described in the Figure 3-6. The top chord is implied to bending and axial compression. Therefore, it is checked for the interaction of both internal forces:

$$\frac{N_{Ed}}{\chi * N_{Rk}/\gamma_{M1}} + \frac{M_{y.Ed}}{\chi_{LT} * M_{y.Rk}/\gamma_{M1}} \leq 1, \tag{6}$$

Where	$M_{y.Ed}$	Bending moment around y-axis
	$M_{y.Rk}$	Bending resistance around y-axis
	N_{Rk}	Compressive resistance in longitudinal axis
	χ_{LT}	Factor for lateral torsional buckling
	χ	Factor for axial buckling.
	γ_{M1}	Partial safety factor

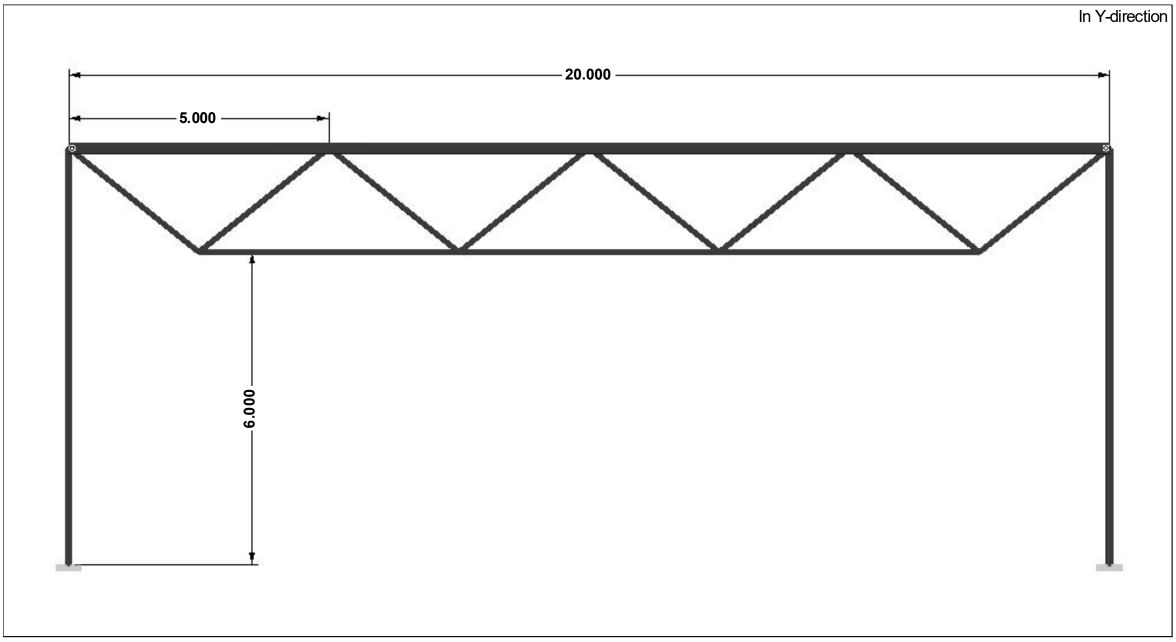

Figure 3-6 Example of a steel frame, modeled in Dubal RFEM. Frame has a span of 20 m, free space of 6 m beneath the truss, bracing every 5 m, base connection rigid, pinned connection between truss and the column, height of the truss L/10 = 2 m.

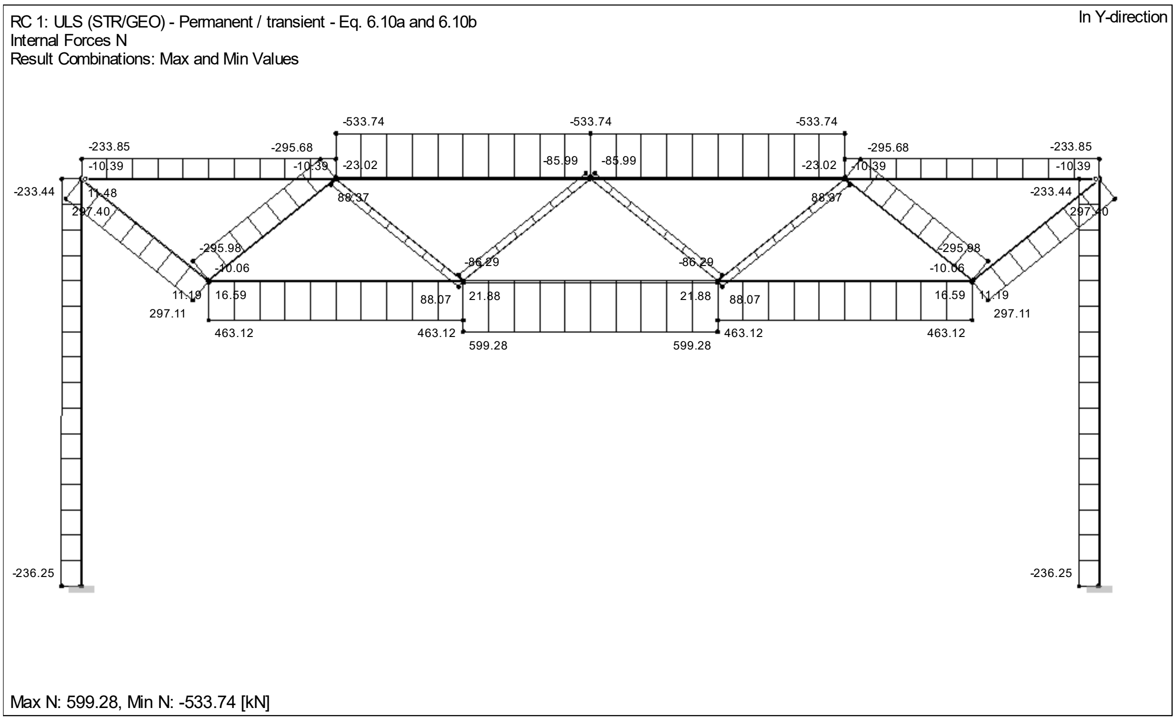

Figure 3-7 Normal forces in a frame 20TRP in ULS, screenshot taken from Dubal RFEM 5.20.

The buckling factors can have a value between 0 and 1. In a case where structure is too slender compared to its length, the possibility for buckling must be checked. The slenderness for axial buckling comes from equation (7):

$$F = \pi^2 * \frac{E * I_y}{L_{cr.y}^2}, \tag{7}$$

Where	F	Buckling force
	I_y	Second moment of inertia in y axis
	$L_{cr.y}$	Effective length for lateral buckling around y axis

The effective in-plane buckling length $L_{cr.y}$ is solved with a factor $k_{cr.y}$. The effective length factors $k_{cr.y}$ are found in buckling modes. The Buckling mode can be solved in stability analysis. The correct factor is in a buckling mode (also known as Eigenvector number) in which top chord fails. Normally the top chord buckles in a lower buckling mode, however, depending on the configuration, the upper chord can buckle at higher modes. The first and eighth eigenvectors are demonstrated in the Figure 3-8 and Figure 3-9. Demonstration of optimization of a truss is shown in the appendix D.

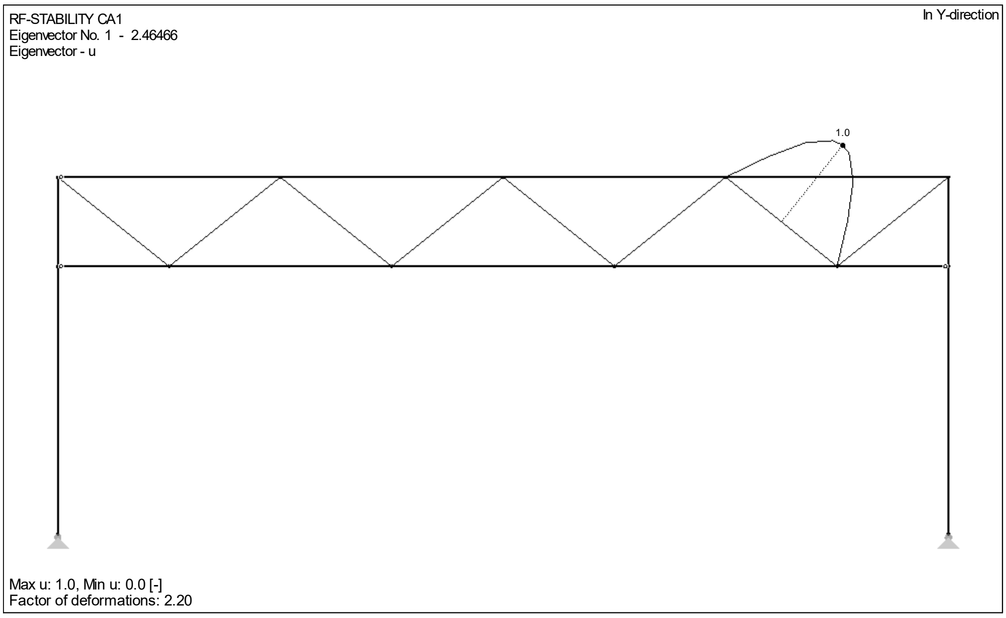

Figure 3-8 Stability analysis showing one of the trusses failing in Eigenvector No. 1 with loading factor of 2.46

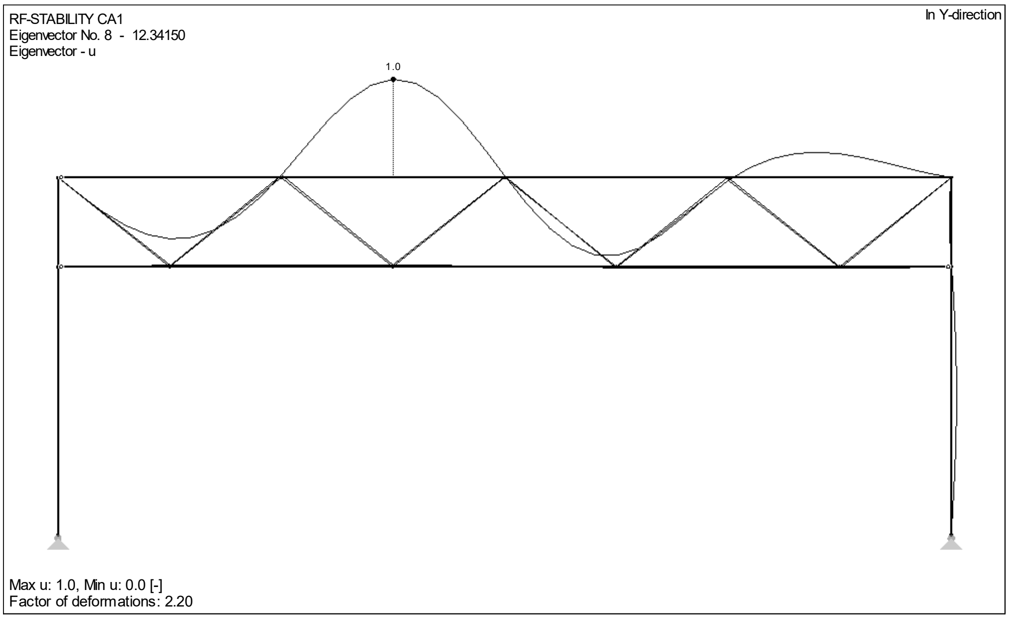

Figure 3-9 Stability analysis showing top chord failing in Eigenvector No. 8 with loading factor of 12.34

Once the $k_{cr.y}$ factor was solved, the top chord was designed according to EN 1993-1-1. Members of the truss were divided into three groups, the top chord, the bottom chord, and the bracings. Each group was optimized separately, see Annex D.

Utilization ratio was optimized to be as high as possible. However, columns had utilization ratio of 0.41-0.98. The priority was in reducing the total weight of the frame. Combined weight of columns and truss was lower than having both with a high utilization ratio. In a case where the column had to be increased, the truss had a possibility to reduce material weight. Trusses had a utilization ratio of 0.8-1.0. Most beams had utilization ratio of 0.95, see Figure 3-10.

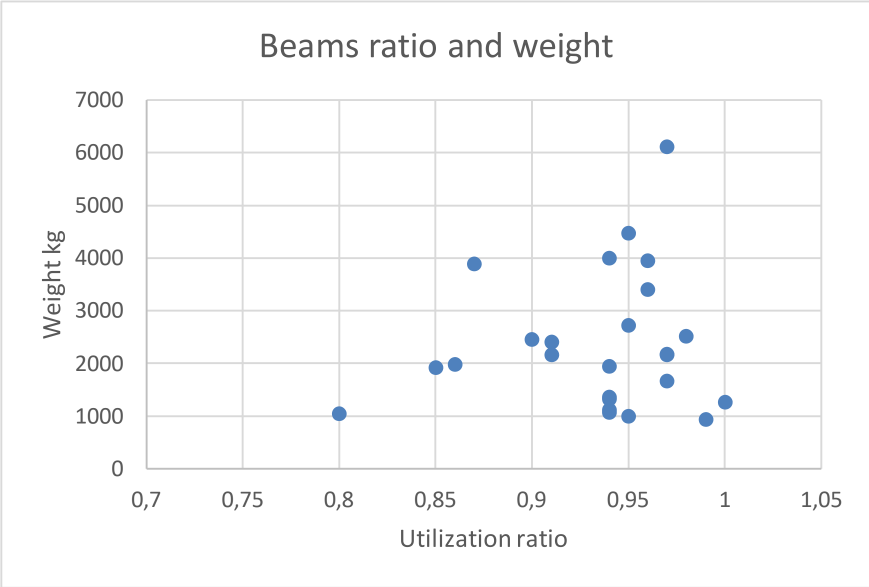

Figure 3-10 Weight of all beams and trusses and their utilization ratio.

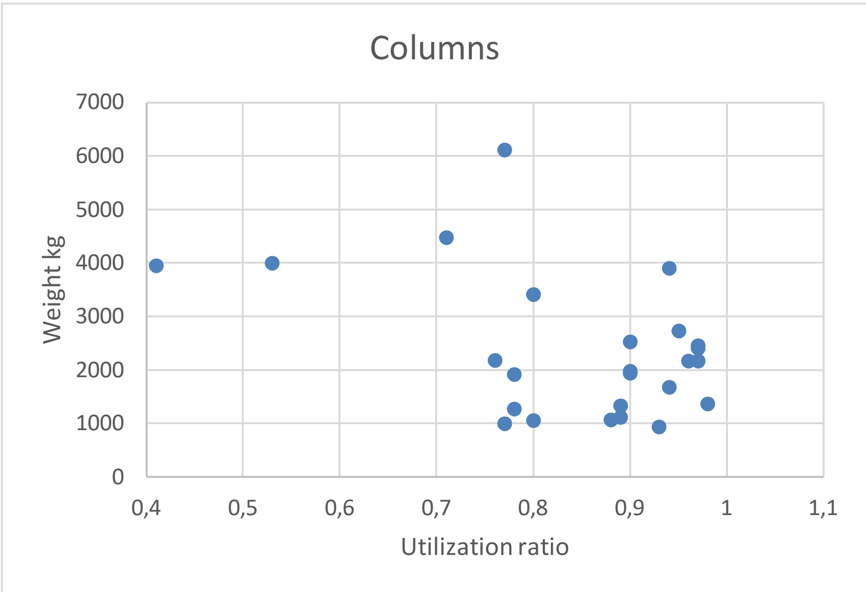

Figure 3-11 Weight of all columns and their utilization ratio.

Connections for trusses were always seated, the connections behave as pinned, due to having no possibilities to transmit tensile forces from the bottom chord to the column. see Figure 3-12. Whereas for the fixed trusses, the bottom chords are connected to the column with a gusset plate, see Figure 3-13. Connections for the tapered trusses were same as for levelled trusses.

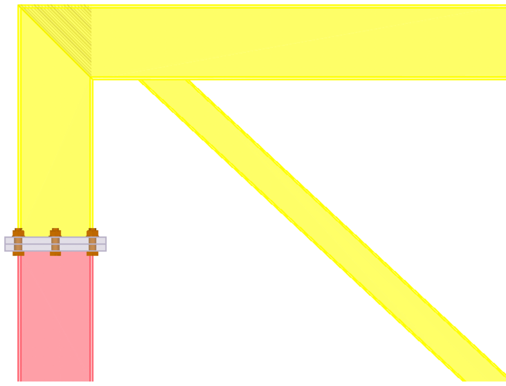

Figure 3-12 Seated truss connection in pinned and rigid frame. HEA column connected to the welded vertical extension of the truss. Extension helps in lowering of the connection and allowing more evenly distributed stressing on the bolts and plates.

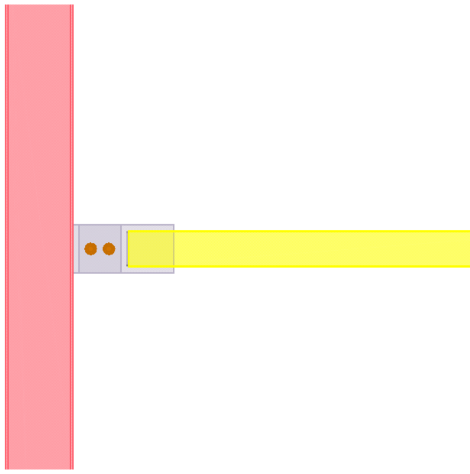

Figure 3-13 Bottom chord connected to HEA column with a gusset plate for the rigid frames. Gusset plate connects to the flange where the web of the column is.

3.3 Frames with a single beam

Haapio's research (2013) considered how the frame's boundary condition's influence the requirements of the members and installation time. Good optimization regarding the GWP would consider the carbon emissions coming from weight of the beam, connection components, footing materials, installation time, and transportation.

For short spans of 10 m and 15 m, the frames are designed with a standardized profile catalog. If a single beam was not able to satisfy the design requirements, it was then turned into a truss. The boundary conditions of a frame were either pined, rigid or semi-rigid. The base connection was pinned only for rigid frame, see Figure 3-14, with pinned beam connection, the base was rigid. The third frame type was fully semi-rigid.

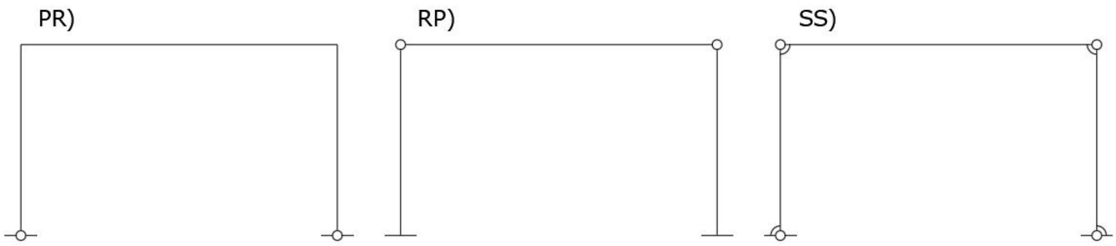

Figure 3-14 PR) rigid frame with pinned base connection. RP) pinned frame with rigid base connection, SS) semi-rigid frame with semi-rigid base.

Rigid frames were compared first with the pinned frames. Then the frames with semi-rigid connections were compared to rigid and pinned frames. Beams with rigid connections have the highest moment in the ends of the beam, while the beams with pinned connections have the highest moment in mid-span. In both cases, rigid and pinned beams, the change in moment was equal to equation (8), see Figure 3-15. By controlling the stiffness of the connection, thus designing it as semi-rigid connection, the moment can be divided equally, see equation (9) and Figure 3-15.

$$\frac{qL^2}{12} + \frac{qL^2}{24} = \frac{qL^2}{8} \tag{8}$$

Where	q	Applied line load
	L	Length of the beam

$$\frac{qL^2}{8} * \frac{1}{2} = \frac{qL^2}{16} \tag{9}$$

Semi-rigid frames are assumed to have the smallest maximum moment in the beam, therefore perform better, see Figure 3-15. The lower moment in the end compared to rigid connection results also in smaller requirements for column's moment resistance, further improving the material requirements. Whereas pinned frames have the highest requirements in the beam, but smallest requirement in columns.

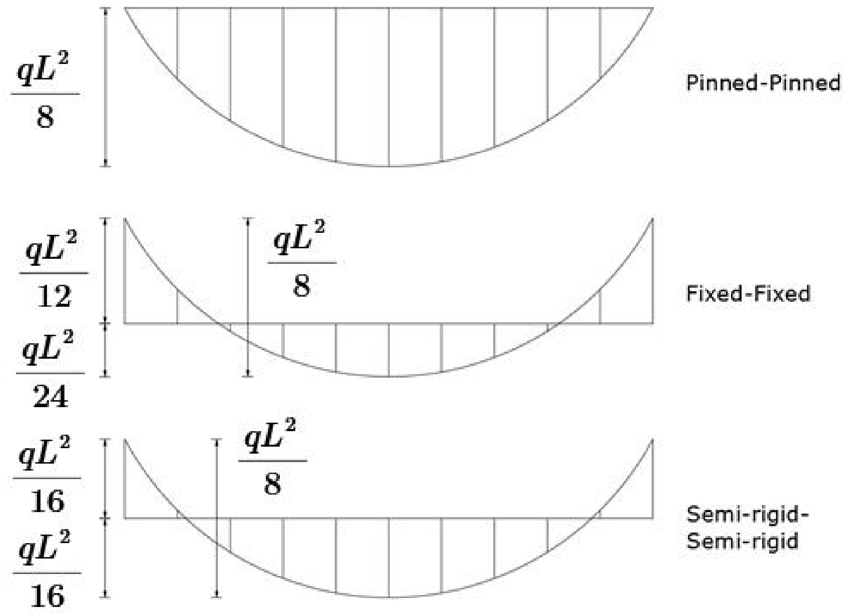

Figure 3-15 Boundary conditions are either Pinned-Pinned, Fixed-Fixed (Rigid-Rigid) or Semi-rigid on both ends. Smallest maximum moment ($qL^2/16$) is found in semi-rigid beam.

3.4 Design of steel connection and footings

Open profiles connected only by the web are interpreted as pinned connections. For tubular profiles pinned connections can be designed as gusset connections as shown in Figure 3-16.

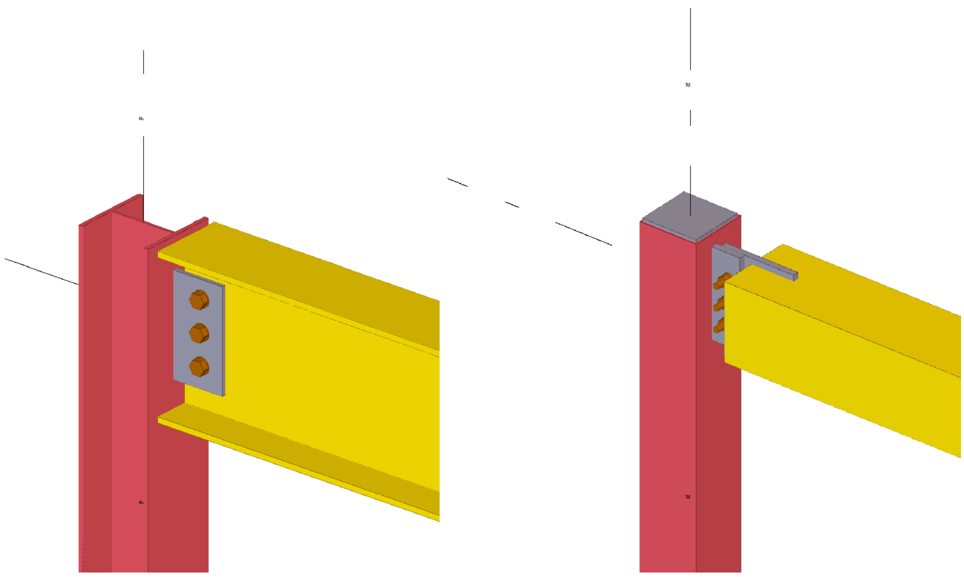

Figure 3-16 On the left the web connection, on the right the tube gusset connection.

Rigid and semi-rigid connections require more adequate verification. The stiffness of the connection determines if the connection is rigid or semi-rigid. The stiffness is measured according to Eurocode 1993-1-8's component method.

Recognizing that most joints have an actual behavior which is intermediate between pinned and rigid joints, Eurocode 3 and Eurocode 4 offer the possibility to account for this behavior by opening the way to what is presently known as the semi-continuous approach. This approach offers the potential for achieving better and more economical structures. (Jaspart et al. 2016, p. 2.)

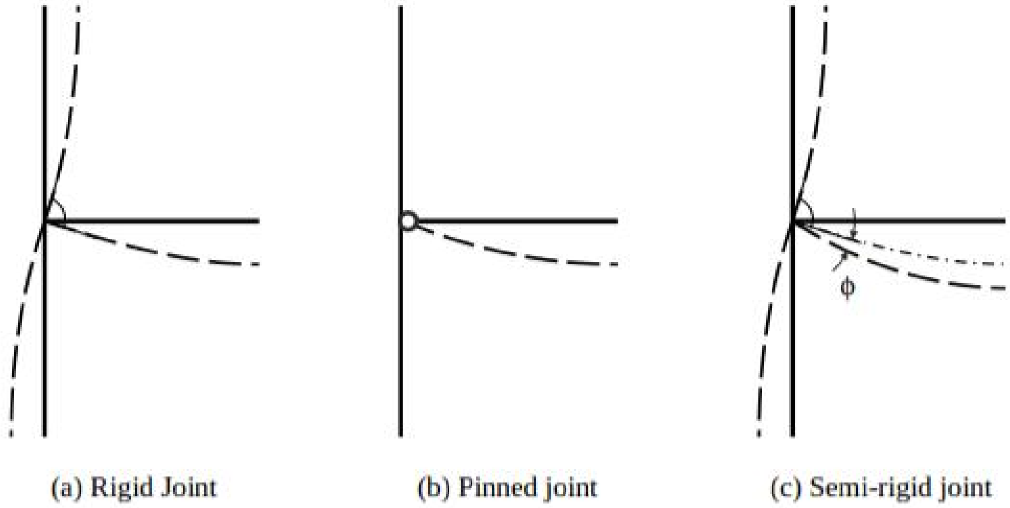

Figure 3-17 Classification of joints according to stiffness (Jaspart et al. 2016, p. 3).

Stiffness between two members is evaluated from moment resistance of the connection $M_{j.Rd}$ and rotation ϕ. The smaller rotation compared to the moment resistance means stiffer connection. Stiffness of the connections $S_{j.ini}$ represents the initial stiffness. In the Figure 3-6, actual M-ϕ curve has a linear part up to 2/3 $M_{j.Rd}$. If the stiffness is close to maximum moment resistance, the $S_{j.ini}$ is corrected with a η factor.

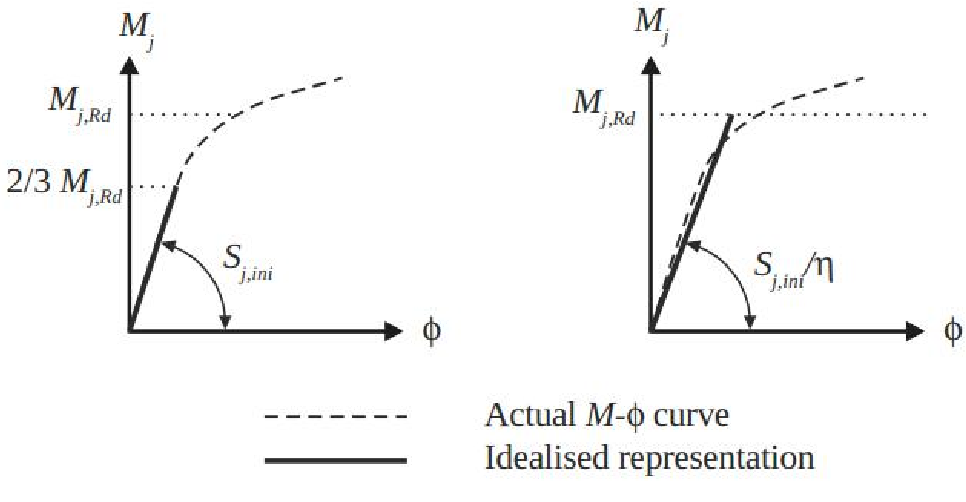

Figure 3-18 Rotational stiffness defined in two different cases according to EN 1993-1-8. (Jaspart et al. 2016, p. 61.)

The moment between column and beam was taken from the rigid frame type. While forces in base are taken from the rigid frame type, see Figure 3-14. After the connection was checked for rigid case in IdeaStatica, the stiffness was gradually reduced, until it was classified as semi-rigid, see Table 3-1. The example if the design process can be seen in Appendix G. The stiffness of the connection is calculated as a sum of components, such as welds, bolts, plates. Strain of each component contributes to rotation relative to the moment arm between the tensioned component and the compression centroid. These strains are presented in EN

1993-1-8 as k-factors. The $S_{j.ini}$ is then a moment arm in power of two divided by the sum of all the inverse values, see equation (10).

$$S_{j.ini} = E * \frac{z^2}{\sum_i \frac{1}{k_i}}, \qquad (10)$$

Where	E	Young's modulus
	z	Moment arm between the centroid of tensile and compressive area
	k_i	Strain factors according to EN 1993-1-8

If the applied moment in the joint is too close to the maximum joint resistance $M_{j.Rd}$, the stiffness is reduced by the μ factor, see (11) and (12). This fixes the uncertainty coming from nonlinearity of the stiffness, see Figure 3-18:

$$M_{j.Ed} \leq \frac{2}{3} M_{j.Rd} \colon \mu = 1\,, \qquad (11)$$

If the implied moment is over two thirds of the maximum moment resistance, for all the connections except for angle steel joints, the final stiffness is reduced according to equation (12) and (13) (SFS-EN 1993-1-8, p.101).

$$M_{j.Ed} > \frac{2}{3} M_{j.Rd} \colon \mu = \left(1.5 * \frac{M_{j.Ed}}{M_{j.Rd}}\right)^{2.7}, \qquad (12)$$

$$S_j = S_{j.ini}/\mu, \qquad (13)$$

The stiffness designs were done in IdeaStatica 10.1. The stiffness analysis directly gave the classification of the connection type and the stiffness value. The stiffness of the base connection was designed in the same program. The forces implied matched the results taken from the RFEM models, see appendix G.

Table 3-1 Connection classes and stiffness from IdeaStatica 10.1. See Figure 3-19 and Figure 3-20.

Open profile	Class	Sj
Beam-to-column connection	Semi-rigid	62,5 MNm/rad
Column base connection	Semi-rigid	5,3 MNm/rad
Tube profile	Class	Sj
Beam-to-column connection	Semi-rigid	45,0 MNm/rad
Column base connection	Semi-rigid	3,0 MNm/rad

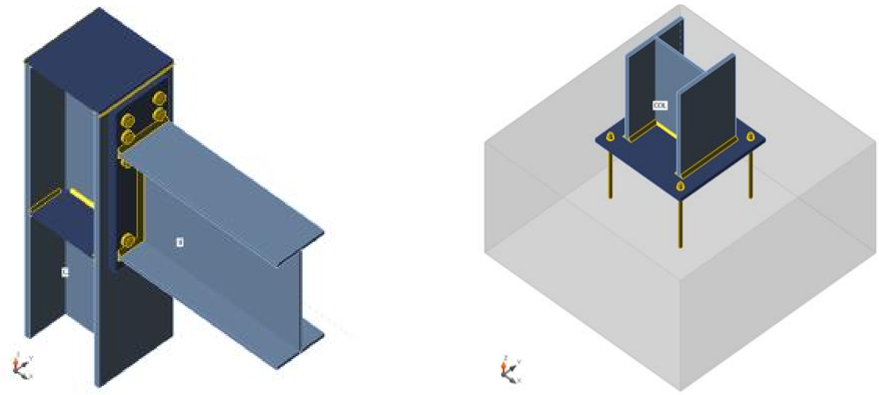

Figure 3-19 Semi-rigid connections designed in IdeaStatica 10.1. for open profiles.

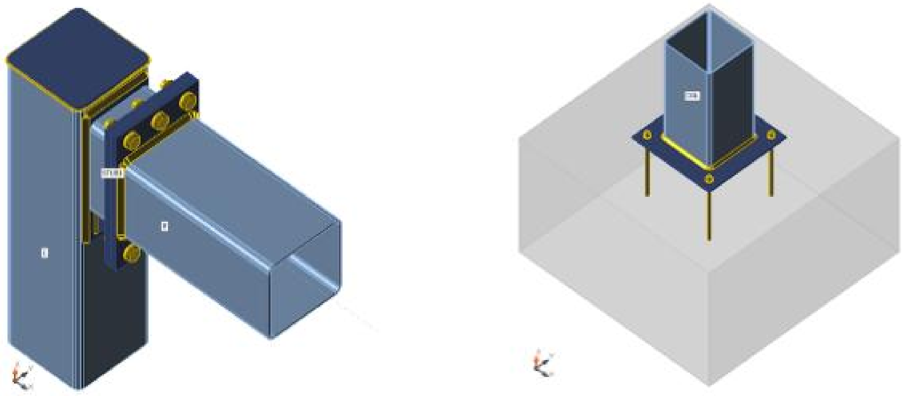

Figure 3-20 Semi-rigid connections designed in IdeaStatica 10.1 for tube profiles.

After designing and verifying connections in IdeaStatica, the $S_{j.ini}$ values were used in RFEM models for semi-rigid frames. The accurate design requires iterations between change of forces and checking that connection can withstand new load distribution. Semi-rigid connection in upper corner reduces the beam size compared to the pinned frame, but it influenced columns requirements. Therefore, columns had to be checked too.

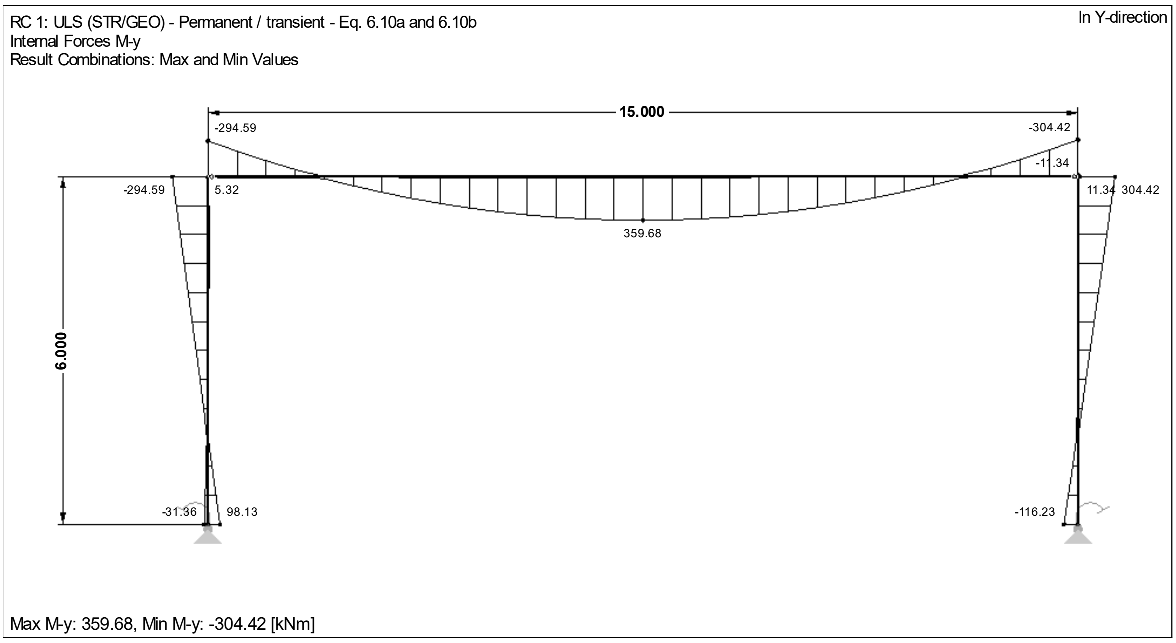

Figure 3-21 15OSS frame in Dubal RFEM 5.20. having semi-rigid connections. Rotational stiffness imported from Idea Statica 10.1.

The foundations of the frames are designed as footings. Footings are made of reinforced concrete, and the overturning is not restrained with piles or anchors. Big moment in the base requires greater dimensions, so the footing can resist the overturning.

Once designs were checked, frames were modeled in Tekla Structures 2018. Tekla models included bracings, connection parts and footings. Footing was designed to withstand overturning coming from moment. For pinned base connection, a smaller footing was possible, due to absence of moment. Footings did not have high utilization rate in other checks, because overturning was the dominant problem in rigid or semi-rigid cases. In a case where frame could not fulfill deflection requirements, the beam was replaced by a truss.

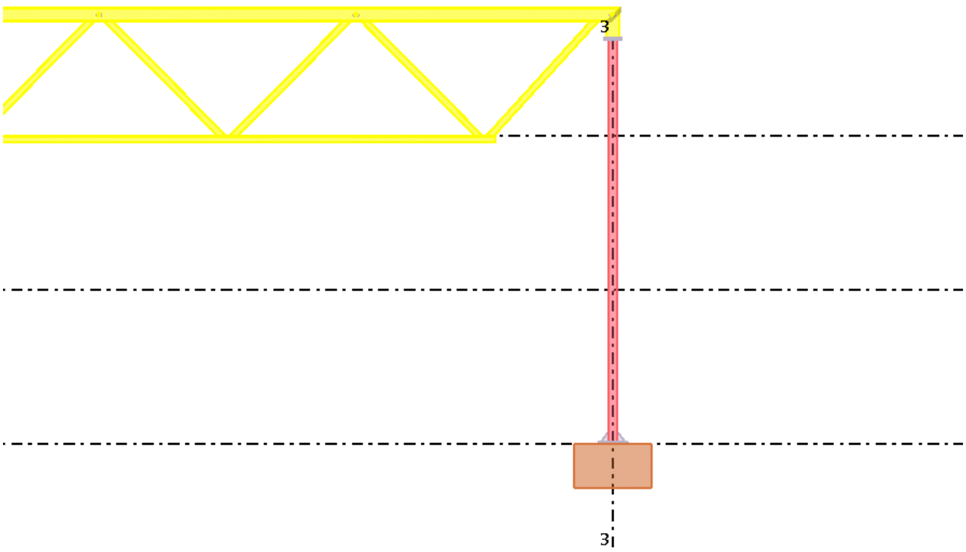

Figure 3-22 Footing of the frame are optimized to withstand the implied loads coming from the column. Model designed in Tekla Structures 2018.

3.5 Design of wooden frames

Virtanen (2020) stated that laminated wood is stronger than steel of similar weight, and modular construction allows for higher wind turbines. In addition to lower emissions, construction of wood will also become cheaper, according to the industry, because it is a cheaper material than steel.

Wood beams in this analysis were either double-tapered or rectangular. Double-tapered beams were used in 25 m and 20 m spans. Rectangular beams were used in 20, 15 and 10 m spans. Wood beams and columns were modeled as a Glue Laminated timber with compressive strength of 30 MPa (GL30c).

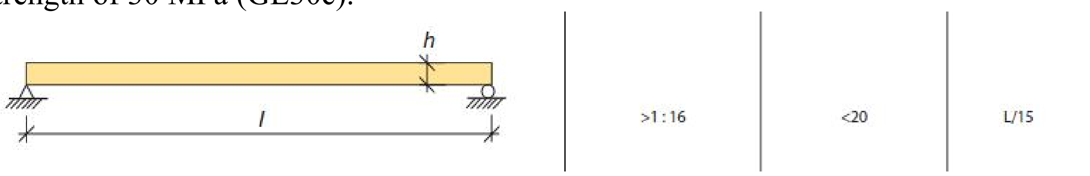

Figure 3-23 A beam with constant profile can be used up till 20 m with the height recommendation L/15. Roof slope required to be over 1:16 (Riipola et al. 2015, p. 3-18).

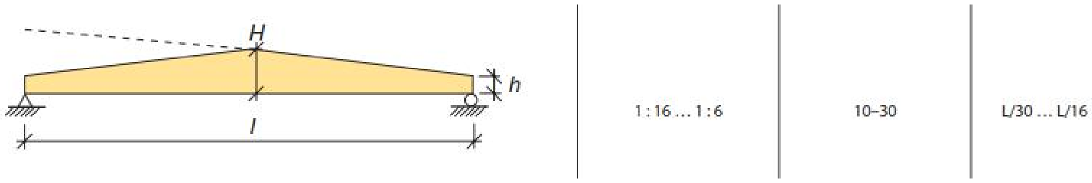

Figure 3-24 Double-tapered beams are used in the range of 10 to 30 m, max height being at L/16 and roof slope between 1:16 and 1:6 (Riipola et al. 2015, p. 3-18).

Beams were optimized with smallest area that could results from combining the width and the height. The initial diameters were based on the instructions in the Finnish Glue Laminated timber manual 'Liimapuukäsikirja' published by Puuinfo (Riipola & Fonselius, 2015). The internal forces were calculated in RFEM for straight beams, but design check was done in Excel sheets for all the wood members. Design of the beam and the columns were calculated manually by an Excel sheet, see appendix E. Calculations included all the checks that were required in EN 1995-1-1. Columns were designed to be at least as thick as beams, or wider if design required stronger lateral stiffness. The design life of the wood members was set to 100 years.

3.6 Wood connections

Wood connections were based on a reference case. Connections were modeled in a way that they would endure shear forces and allow long life span for the structure. Beams were modeled with free rotation at the ends, therefore, connections had to be designed as pinned type, see Figure 3-26. Wood columns had to be designed with a rigid base connection, which is often referred as a mast column. Therefore, a column shoe was designed to allow the transfer of the moment from the column to the footing without breaking the base of the column, see Figure 3-25. Columns are reinforced with rods and steel plate which are anchored via column shoe to the footing.

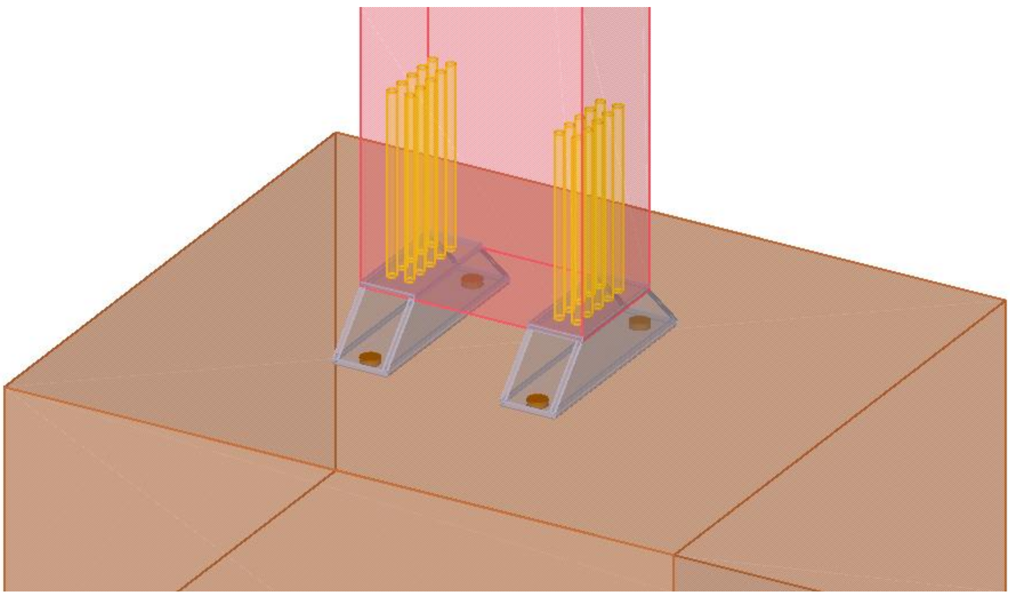

Figure 3-25 Column shoes in the base of the wooden column with 4 anchors of 30 mm and reinforcing rods of 20 mm diameter and length of 400 mm. Modeled in Tekla Structures 2018.

Wood structures requires evaluation of creep over time. Wood can withstand higher loads for a short time, but can start to deform under permanent load, even if load is much smaller than short time load. In this analysis, loading consisted of self-weight, snow load, and wind load. Each load had their specific load factor, as specified in EN 1994-1-1. The calculation for the wood beam and column is presented in appendix E.

Connection plates could have been made of wooden parts, but the plates are prone to cracking. Typically, connections are made of steel parts, ensuring that cracking does not occur during the long-life service. Bolts are connected through the beam and column. Connection can be interpreted as pinned connection because moment cannot be transferred through lateral connections. Bracings are connected to the beam with L-plates on both sides. Typically, stiffening bracings are made of steel members or cables. In this analysis, bracings have been left out as the model only studies 2D frames. For wooden frames however, lateral restraints were made of wooden planks as show in Figure 3-26.

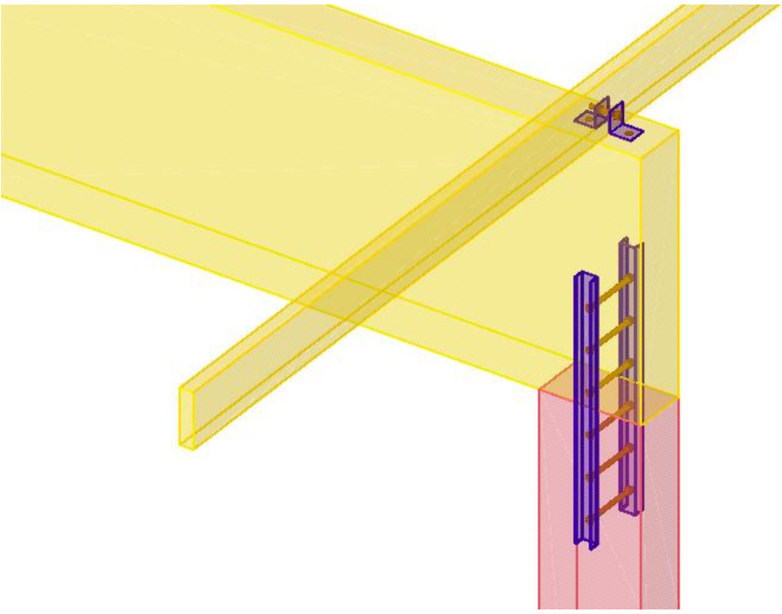

Figure 3-26 Connections in upper corner. Modeled in Tekla Structures 2018. Reinforcements filtered out form the picture.

One of the concerns was the contact between column and the beam. Wood beams typically are reinforced with steel plates to avoid crushing of the beam. Steel plates are often connected to the beam by drilling 21 mm holes and gluing 20 mm steel rods in the beam as shown in Figure 3-27. The rods also work as a reinforcement for the wood in the compressive area. Rods help to distribute the high shear force, so the edge between the beam and the column does not crash over time.

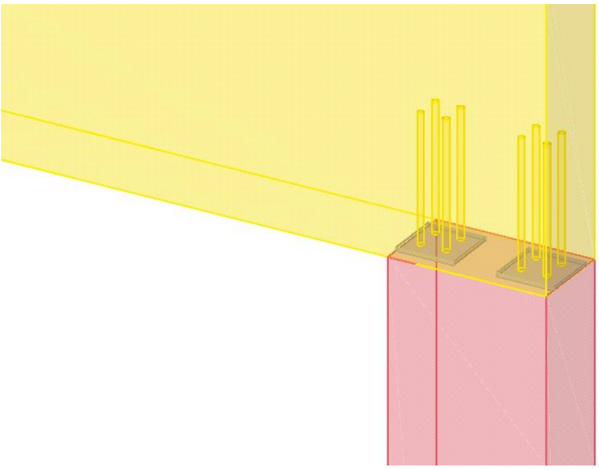

Figure 3-27 Contact between column and beam is reinforced with steel plate and steel rods of diameter 20 mm and length 400 mm. Modeled in Tekla Structures 2018, bolt connection filtered out form the picture.

3.7 Material lists

Material lists were generated from Tekla models. The material list consisted of the weight of each component of the frame, which made it possible to divide the members into their own groups. Bolts were counted separately with a filter in Tekla Structures. For steel structures the bolts were modeled as M20 with the length of 100 mm. Wood frames used longer bolts which were based on the thickness of the beam, see Figure 3-26.

Welding length were taken from Tekla connections with Multi Report Generator. Multi report showed every weld size and length separately, but for simplicity, the weld size was rounded up to an average size.

The weight of the footing was calculated in Excel sheet based on the dimensions of the footing. The weight of the reinforcements was calculated according to design results of each footing.

3.8 EPD-reports

This analysis will consider modules A1-A3, A4-A5, C1-C4 and module D. Modules A1-A3 were collected from available EPD-reports found from product manufacturers webpage. EPD-reports for wood products included also information of C1-C4. Bolts, welding wire and anchors were collected from EPD library found in One Click LCA. GWP of reinforcements were collected from One Click LCA database.

GWP's factors were gathered into an Excel sheet. Many reports had to be interpreted properly to understand how the values were estimated. The EPD-reports were very different and required some unification of units. For example, most wood manufacturers presented GWP values either as kg CO_{2eq}/m^3 or as kg CO_{2eq}/kg. In some EPD-reports the basic unit was given in tons or cube meters. In this study the units were converted to represent embodied carbon per kilogram of a product.

Modules D were taken as they were presented in reports. Basically, module D for steel products was based on proportion of recycled scrap metal to virgin metals. The contribution in this study represents how much of carbon emissions have been avoided.

For many wood reports, the module A1 which represents acquiring of raw materials, had a negative value for footprint. This is due to instructions in SFS-EN 16485, where biogenic carbon within system is released on the later stages of the life, see Figure 3-28. Assumption suggests that cutting down technology and timber preparation reduces emissions from atmosphere. The module C3 represent the release of carbon emissions.

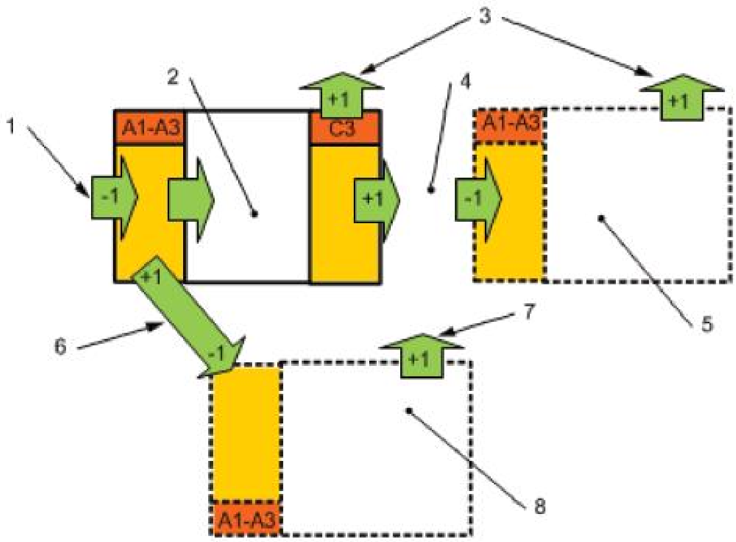

Figure 3-28 Characterization of biogenic carbon fluxes in stored wood (SFS-EN 16485 p. 13).

1. Transfer of biogenic carbon from the forest to the product system
2. Product system under study
3. Emission into atmosphere
4. Recycled wood
5. Subsequent product system
6. Co-product
7. Emissions into atmosphere
8. Parallel product system

It is worth mentioning that in case that harvested trees were not cultivated, it would count as deforestation and therefore reducing the actual carbon storages. Cultivating trees should be seen more like necessary compulsion to achieve sustainability in the industry. Otherwise in the worst scenario the virgin material causes deforestation, and if the product is not recycled nor utilized for energy production, it becomes a disposable waste.

3.8.1 EPD library for materials

Because the material lists can be extracted easily from Tekla Structures, the material information in EPD-report should be converted to a unified unit, so when multiplying with the total mass of a certain component, the unit becomes then kg CO_{2eq}. Simply by multiplying the mass of products with the unit in modules A1-A3 + C1-C4 should result in total embodied carbon:

$$P\ [kg] * F \left[\frac{kg\ CO_{2eq}}{kg}\right] = G\ [kg\ CO_{2eq}]\ , \tag{14}$$

Where P Mass of the product
F GWP factor for 1 kg of a product
G GWP

For this study, the wood emissions were comparable with steel by including the release of biogenic carbon in module C1-C4 as shown in Table 3-2.

Table 3-2 material factors collected from EPD-reports from steel and wood manufacturers.

	unit	A1-A3 + C1-C4	D
Cold formed tube	kg CO2e/kg	2,83	-1,40
Hot rolled profile	kg CO2e/kg	2,71	-1,30
GL timber	kg CO2e/kg	0,42	-0,73
Steel plate	kg CO2e/kg	2,71	-1,48
Concrete C28/35	kg CO2e/kg	0,09	0

3.8.2 GWP of welds

Welding length was taken from Tekla Structure's Multi Generator for welds. For a rectangular equilateral triangle, the surface area of the cross-section is a squared. Weight of weld is counted separately in the Excel sheet as:

$$a^2 * L * 7{,}85 * 10^{-6} \frac{kg}{m^3}\ , \tag{15}$$

Where L Total length of the weld
a Throat thickness, see Figure 3-29

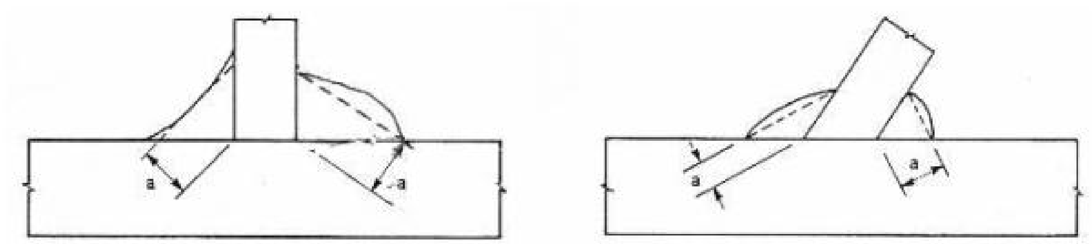

Figure 3-29 Definitions for weld throat thickness a (EN 1993-1-1, p.45).

The additional GWP from protection gas is also included in the multiplayer factor. The most common welding gas in MIG welding has a mixture of 18 % CO_2 and 82 % Argon. The average consumption is 18 l/min. To combine the previous information, we need to estimate the mass of the gas. The ideal gas is defined as 22,4141 liter/MOL where 18% of the mass is CO_2:

$$C + O_2 = \frac{12.001g}{MOL} + 2 * \frac{15.999g}{MOL} = 43.999 \frac{g}{MOL}, \tag{16}$$

$$0.17 * 43.999\ g/MOL = 7.48\ g/MOL\ , \tag{17}$$

$$18\ l = 6\ g\ CO_2/\min\ , \tag{18}$$

$$18\ l = 0.006\ kg\ CO_2/\min\ , \tag{19}$$

As the welding gas has 0.33 g CO_{2eq}/l, the 18 liters per minute produces 0.006 kg CO_{2eq}. The welding time is evaluated according to regression of installation times from (Haapio, 2012, p. 67), see Appendix A:

$$t = L * (0{,}4988 * a^2 - 0{,}0005 * a + 0{,}0021)\ min\ , \tag{20}$$

Where L Total length of the weld
a Throat thickness

3.8.3 GWP of footings, reinforcement, and steel rods

Reinforcement is calculated with the same Excel sheet as footing, see appendix F. The same GWP was used for rods that are reinforcing timber connections. Reinforcement is not usually made from virgin steel. According to One Click LCA, 97 % of reinforcement is typically made of scrap steel.

In addition, every bolt adds some emissions per unit. Most common bolt in this analysis was M20 which weights 341 g and has a total GWP of 0,89 kg CO2e/unit.

3.8.4 Transportation in module A4

Module A4 considers GWP coming from transportation. In this analysis, distance from factory or storage to the site is set to 200 km, assuming that all the products are ordered from a nearby manufacturers. Delivery is done with 40 t semi-trailers which have max capacity of 25 t. Trailers are loaded with 80 % from full capacity. Trailer trucks will also return 200 km, but with an empty cargo.

	CO_{2e} [g/km]		CO_{2e} [g/tkm]	
Emission standard	Empty	fully loaded (25t load)	partially loaded (e.g. 70%)	fully loaded (25t load)
--> 1992	657	946	49	38
EURO I (1993 - 1996)	637	926	48	37
EURO II (1997 - 1998)	628	974	50	39
EURO III (1999 - 2003)	630	976	50	39
EURO IV (2004 - 2007)	625	960	49	38
EURO V (2008 - 2013)	636	971	50	39
EURO VI (2014 -->	628	880	46	35
Average in 2016	**630**	**962**	**49**	**38**

Figure 3-30 Emissions for 25 t trailer truck. In the middle the emissions per kilometre and on the right emissions per one ton of products per kilometre.

Values are collected from LIPASTO (2017) database. For every ton of products, fully loaded truck emits 38 g CO_{2eq}/tkm and partially loaded (70 %) emits 49 g CO_{2eq}/tkm, see Figure 3-30. Value for 80 % load is calculated via interpolation.

$$38 + \frac{49 - 38}{3} = 41.6\ g\frac{CO_{2eq}}{tkm}, \tag{21}$$

$$41.6\ g\frac{CO_{2eq}}{tkm} * 20\ t = 832 * g\frac{CO_{2eq}}{km}, \tag{22}$$

Loaded truck produces 832 g CO_{2eq} per kilometre. Empty truck produces 630 g CO_{2eq} per kilometre. Then back and forth trip produces a combine's emissions of 630 + 832 g CO_{2eq}/km. For each ton of products, the share is then 73.1 g CO_{2eq}/km. As the distance for all frames is set to be 200 km, that gives us easy to calculate factor:

$$(832 + 630)\mathrm{g}\frac{\mathrm{CO2eq}}{\mathrm{km}} * \frac{200km}{20t} = 0.01462\ kg\ CO_{2eq}/kg, \tag{23}$$

3.8.5 Emissions in module A5

Module A5 represents the emissions coming from installation of the frame on situ. In this analysis only the emissions coming from crane operating time per frame, see equation (24). The evaluation method is based on regression analysis from (Knuuttila, 2011), see Annex B.

$$0{,}5 * b - 0{,}42\ min, \tag{24}$$

Where b total amount of bolts

The energy for using crane and man lift were calculated from LIPASTO (2017) report. The average consumption for a crane is 99 kW and for a manlift 33 kW. The crane produces 828 g CO2e/kWh; therefore:

$$(99 + 33)\ kW * 828\ \frac{g\ CO_{2eq}}{kWh} = (109.296)\ \mathrm{kg}\frac{\mathrm{CO}_{2eq}}{\mathrm{h}}, \tag{25}$$

3.8.6 Benefits in module D

The rebars did not have module D evaluated, in this study the handprint was based on reduced consumption of recycled material. According to One Click LCA, 97% of rebar iron comes from scrap metals and GWP of such a rebar is 0,5 kg CO2e/kg. Virgin rebar was reported to have a GWP of 2,89 kg CO2e/kg, therefore D of recycled rebar should be the avoided emissions:

$$\left(0.5\ \mathrm{kg}\frac{\mathrm{CO2e}}{\mathrm{kg}} - 2.89\mathrm{kg}\frac{\mathrm{CO2e}}{\mathrm{kg}}\right) * 0.97 = -2.3183\ \mathrm{kg}\frac{\mathrm{CO2e}}{\mathrm{kg}}, \tag{26}$$

4 Results

Each frame has a unique code, based on the length of the span, the profile type or material type and boundary conditions. For example, see Table 4-1. numbers represent the length of the span, first letter describes the profile type, second letter represents connection type in the base while the last letter represents connection type between the column and the beam.

Table 4-1 Explanation of identification codes in this analysis

Span length	Profile type	Column base	Beam connection	Extra mark
10, 15, 20, 25	O, T, GL	R, P, S	R, P, S	H

1. Span length
    a. 10 m
    b. 15 m
    c. 20 m
    d. 25 m
2. Prolife types
    a. O = open profile
    b. T = Truss/Tube
    c. GL = Glue laminated timber
3. Column base connection
    a. R = Rigid
    b. P = Pinned
    c. S = Semirigid
4. Beam-to-column connection
    a. R = Rigid
    b. P = Pinned
    c. S = Semirigid
5. Extra mark
    a. H = Ridge in the mid-span

For example, 20TRP means a 20 m truss with rigid base connection and pinned top connection. Because all wood frames will be designed as pinned frames, the identification code will be shortened to span length and profile type, for example to 20GL or 20GLH.

The GWP assessment was done to all frames. The total GWP represent the embodied carbon of all the sources. The main sources are of three types. Members which represent the beams, tubes and trusses make the main body of the frame. Second group consists of other frame related components such as footing, fasteners and welds. The embodied carbon in both groups is comes from manufacturing of materials, meaning modules A1-A3, or disposal of the material, meaning module C1-C4. Third GWP source is related to modules A4 and A5. Reason to separate these modules, was related to the question regarding their contribution to the total GWP. However, when total GWP is presented, it includes all the relevant materials and modules. Module B is excluded, due to fact, that all frames were designed for 100 years design life. Members are assumed not to need repairing or maintenance during their operational time. An example of assessment process is shown in Table 4-2.

Table 4-2 Example of member calculation for 10 m wood frame and 10 m open profile rigid frame. Weight of members are assessed in each module separately. Modules and GWP represent kg CO_{2eq}.

	Weight [kg]	A1-A3	A4	A5	C1-C4	D	GWP
Wood members	1371,10	-1782,43	20,05	16,54	2363,15	-544,33	617,30
Steel members	939,30	2536,11	13,73	24,74	0,00	-1221,09	2574,58

The total GWP of glue laminated timber and S355J2 steel in Table 4-2 shows, that steel members have over four times higher GWP than wood members. Steel has also over two times higher value for benefits in module D. However, when comparison includes all sources of emission, including footing, reinforcements, plates and fasteners, the total GWP of same steel frame is around 2.2 times higher, see Table 4-3. This indicates that components of the frame even out the total GWP.

Table 4-3 Example of frames 10-GL and 10-OPR. All components of the frame included. Units are given as CO_{2eq}. Explanation of symbols below the table. Modules A4 and A5 include all components combined.

M	W	A4	A5	B	F	P	A	R	D	GWP
576,1	103,8	58,9	16,5	32,2	220,5	298,1	54,6	50,5	2510,3	1411,1
2536,1	122,4	26,3	24,7	25,0	67,8	234,9	54,6	7,0	2344,9	3098,8

Where	M	Members
	W	Welds
	A4	Module A4 for transportation (all materials)
	A5	Module A5 for installation (all materials)
	B	Bolts
	F	Footing
	P	Plates
	A	Anchors
	R	Reinforcement
	D	Module D

4.1 GWP of frames

The results were comparable. Relative proportions outline how significant each part was to the total GWP. Members were most important contributor source of emissions. But their share varied a lot among the frames. This could be explained by the volume of the members based on their frame model. Moreover, connection plates were increased according to required stiffness.

Table 4-4 Total GWP [kg CO_{2eq}] of the frames and proportion of components.

Module	A1-C4	A1-A3 + C1-C4				A4	A5	A1-A3 + C1-C4		
Unit	[kg]	[kg CO_{2eq}]				[kg CO_{2eq}]	[kg CO_{2eq}]	[kg CO_{2eq}]		
Name	Total GWP	Members	Footing	Plates	Welds	All components	All components	Bolts	Anchors	Rebars
10-GL	1416,0	41 %	16 %	21 %	7 %	4 %	1 %	2 %	4 %	4 %
10-OPR	3098,8	82 %	2 %	8 %	4 %	1 %	1 %	1 %	2 %	0 %
10-ORP	3741,1	76 %	6 %	11 %	2 %	1 %	0 %	0 %	1 %	1 %
10-OSS	3697,4	73 %	10 %	8 %	3 %	2 %	1 %	1 %	1 %	1 %
10-TPR	4123,2	77 %	2 %	17 %	2 %	1 %	0 %	0 %	1 %	0 %
10-TRP	4154,3	73 %	5 %	14 %	3 %	1 %	0 %	0 %	1 %	1 %
10-TSS	4762,0	76 %	8 %	10 %	2 %	2 %	0 %	0 %	1 %	1 %
15-GL	2024,9	53 %	14 %	16 %	5 %	4 %	1 %	2 %	3 %	2 %
15-OPR	6040,6	87 %	2 %	6 %	3 %	1 %	0 %	0 %	1 %	0 %
15-ORP	6399,4	81 %	4 %	9 %	3 %	1 %	0 %	0 %	1 %	0 %
15-OSS	6972,7	77 %	8 %	8 %	2 %	2 %	0 %	0 %	1 %	1 %
15-TPR	7024,6	87 %	1 %	8 %	1 %	1 %	0 %	0 %	1 %	0 %
15-TRP	4934,7	76 %	6 %	10 %	4 %	1 %	0 %	0 %	1 %	0 %
15-TSS	8702,6	78 %	7 %	10 %	1 %	2 %	0 %	0 %	1 %	1 %
20-GL	3539,3	54 %	22 %	9 %	3 %	6 %	1 %	2 %	2 %	3 %
20-GLH	3283,2	50 %	24 %	10 %	3 %	6 %	1 %	2 %	2 %	3 %
20-TPR	7935,5	88 %	1 %	6 %	2 %	1 %	0 %	0 %	1 %	0 %
20-TPRH	7949,2	78 %	10 %	6 %	2 %	2 %	0 %	0 %	1 %	1 %
20-TRP	8179,8	75 %	10 %	9 %	2 %	2 %	0 %	0 %	1 %	1 %
20-TRPH	5840,1	81 %	2 %	12 %	2 %	1 %	0 %	0 %	1 %	0 %
25-GLH	4325,2	60 %	18 %	8 %	4 %	5 %	1 %	2 %	1 %	2 %
25-TPR	12476,6	90 %	1 %	5 %	2 %	1 %	0 %	0 %	0 %	0 %
25-TPRH	12631,9	90 %	1 %	5 %	2 %	1 %	0 %	0 %	0 %	0 %
25-TRP	9823,3	79 %	8 %	8 %	2 %	2 %	0 %	0 %	1 %	1 %
25-TRPH	11862,3	81 %	7 %	7 %	2 %	2 %	0 %	0 %	0 %	0 %

The visual representation helped in comparison. The total GWP of all the frames is presented in Figure 4-1. The total GWP shows components without A4 and A5 modules, as the modules were presented as transportation and installation.

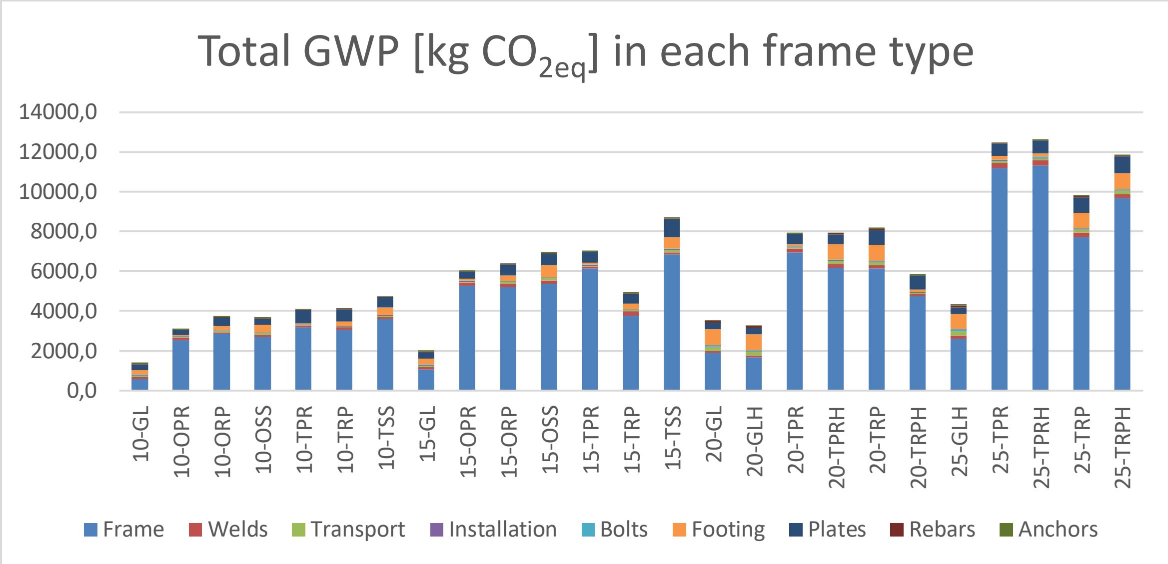

Figure 4-1 The total GWP of each frame from all the sources.

Among steel frames, pinned base connection requires higher material usage compared to other parts. Pinned base connection had significantly smaller footing than other cases, which also increased the relative share of the members. If comparing total emissions, the open profiles generally performed better than tube profiles. This can be explained with efficiency of the geometry. While the rectangular profile is more resistant to lateral torsional buckling, the I-shaped profile has greater bending resistance. In the cases presented in this study, lateral restraints were assumed in every 5 meters, allowing I-profiles to perform well. This study did not compare rectangular profiles of same steel strength as open profiles. Decreasing the strength of the steel would increase the weight of the material.

It can be noticed, that 25TRP has exceptional result among 25 m spans steel frames. Also, 20TRPH and 15TRP had exceptional result in their group span lengths. In this study, rigid base connection with pinned top connection had lower GWP than other frame types.

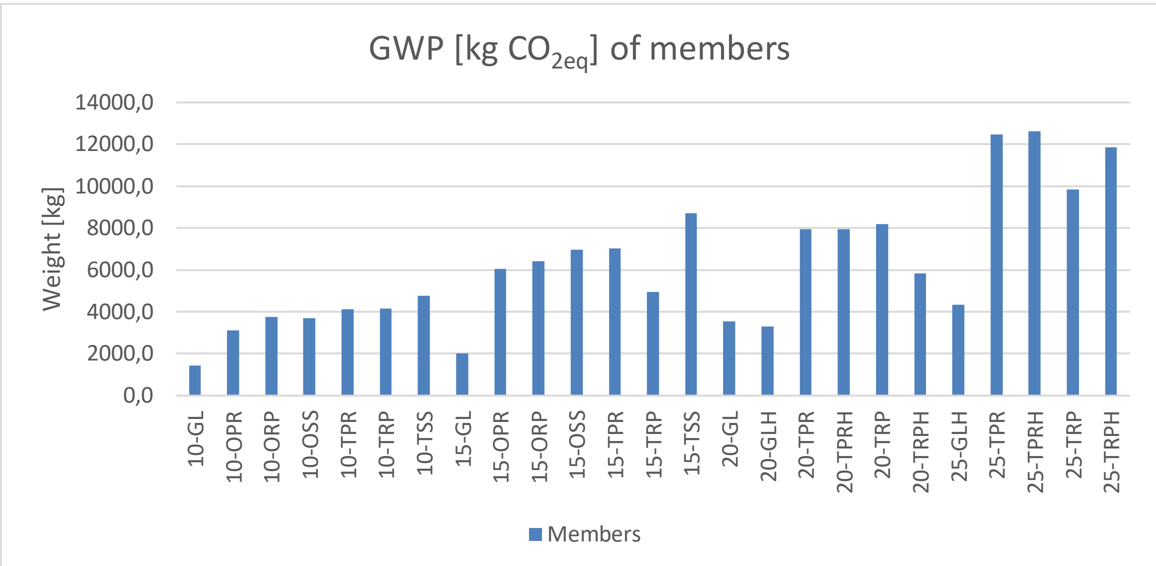

Figure 4-2 Carbon emissions coming from members. Modules A1-A3 and C1-C4.

Members were responsible for most of the emissions. The longer spans had greater relative variations between the total GWP of the members. When comparing other components in Figure 4-3, only plates, footings and welds had a significant impact to the total emissions.

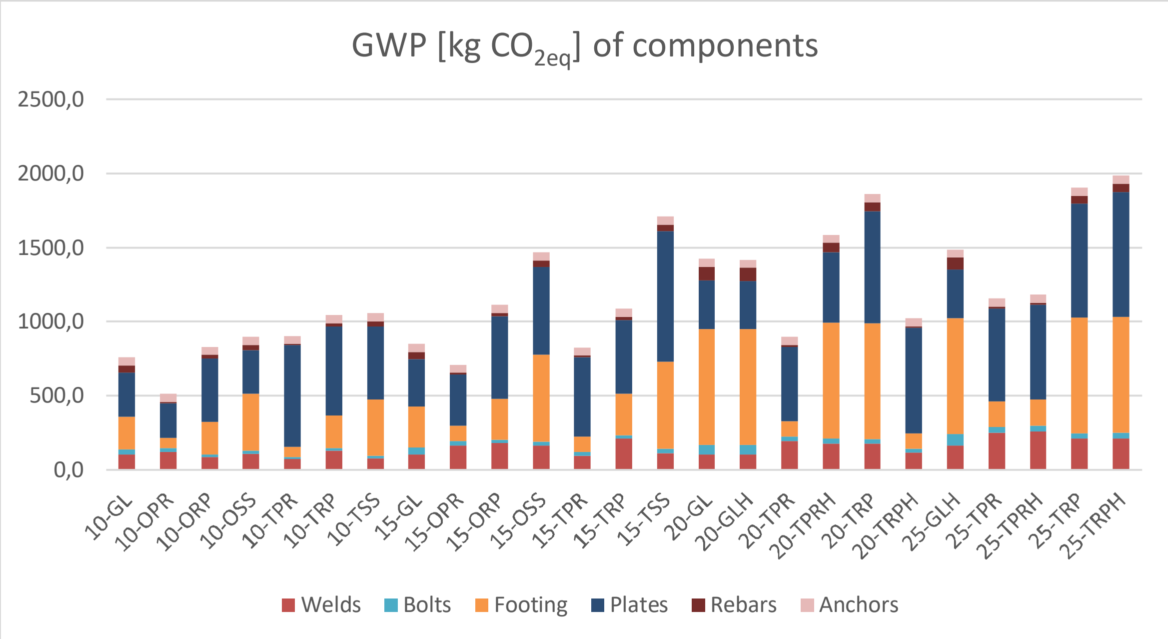

Figure 4-3 Comparison of other parts of the frame. Modules A1-A3, A4-A5 and C1-C4.

The components in this study had bigger variations in longer spans. Some of the 25 m spans had similar emissions as 10 m. Most significant contributors were welds, footings, and plates, which were compared separately in Figure 4-4. The size of the footing increased rapidly, as the volume of the footing grew in volume.

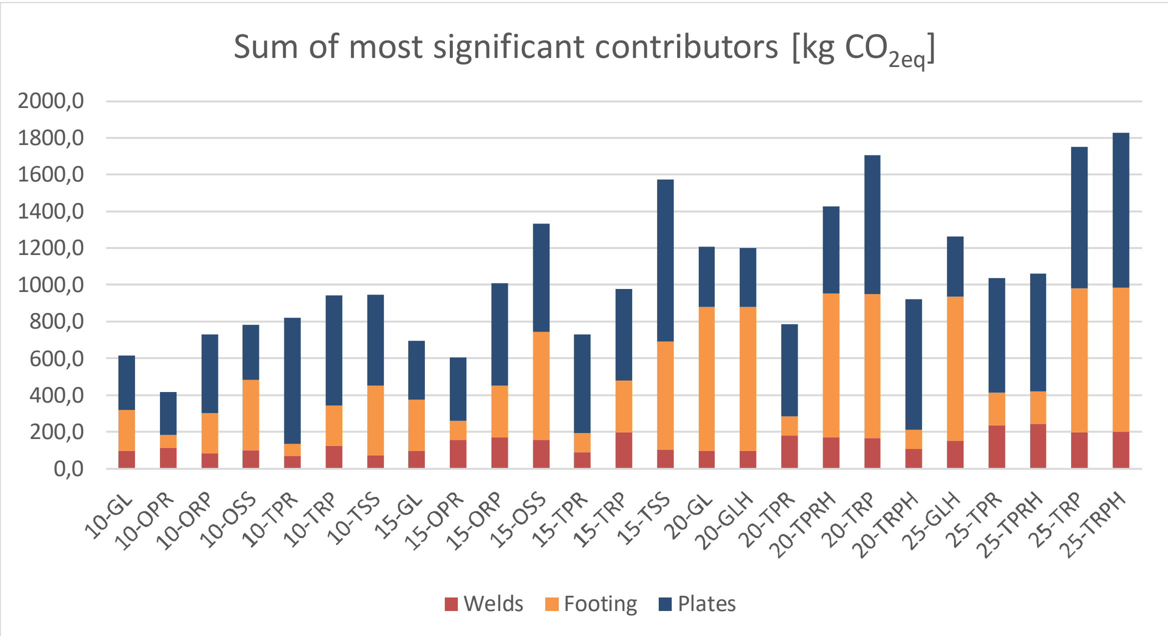

Figure 4-4 The most significant contributors to GWP after the members were welds, footing and plates.

Comparison shows, that even if emission were reduced from footing, requirement of plates and welds increased. While having a pinned connection seems like a good way to lower emissions, the frame ends compensating for the lack of stiffness, therefore designing smaller foundations does not reduce the total outcome nor does it the other way around.

What was surprising to longer spans, wooden beams had a lower mid-span height than the steel trusses. A lower height of the beam is a great competitive advantage when thickness of the sealing is restricted.

In this analysis module D of wooden frames seemed almost equal to total GWP even for wooden frames in shorter spans.

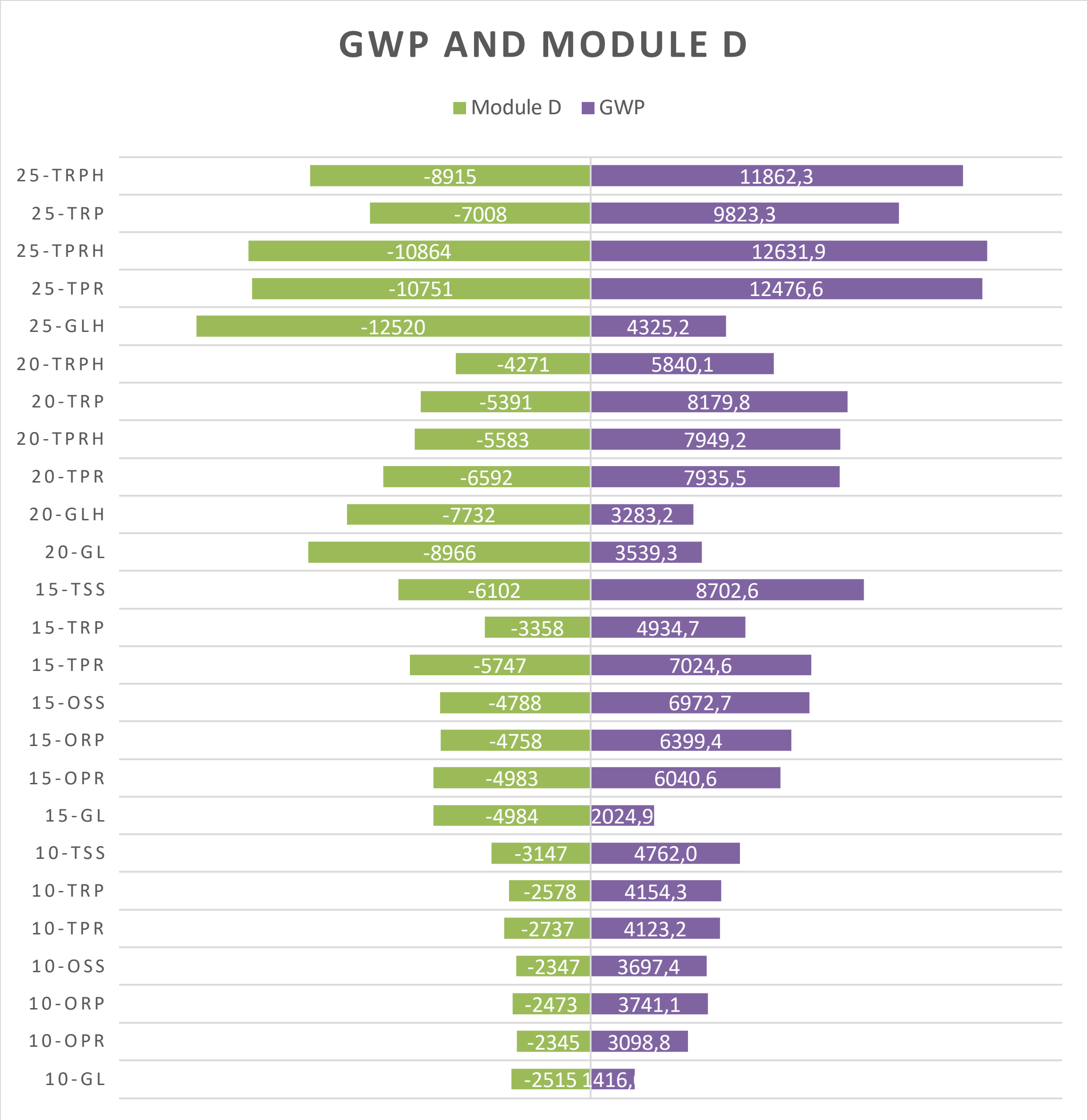

Figure 4-5 Module D compared to GWP.

In this study, the wood frames were designed to serve 100 years as did the steel structures. Commonly, wooden frames have had service time of 50 years, which would mean not only doubling the footprint, but also LCC and disruption in operational time. A break in operating time would add to the WLC (whole life costing) price, as the building would be not in use during the required renovation. However, new wood products promise one hundred years of service life. Therefore, the frames were compared for the same period of use.

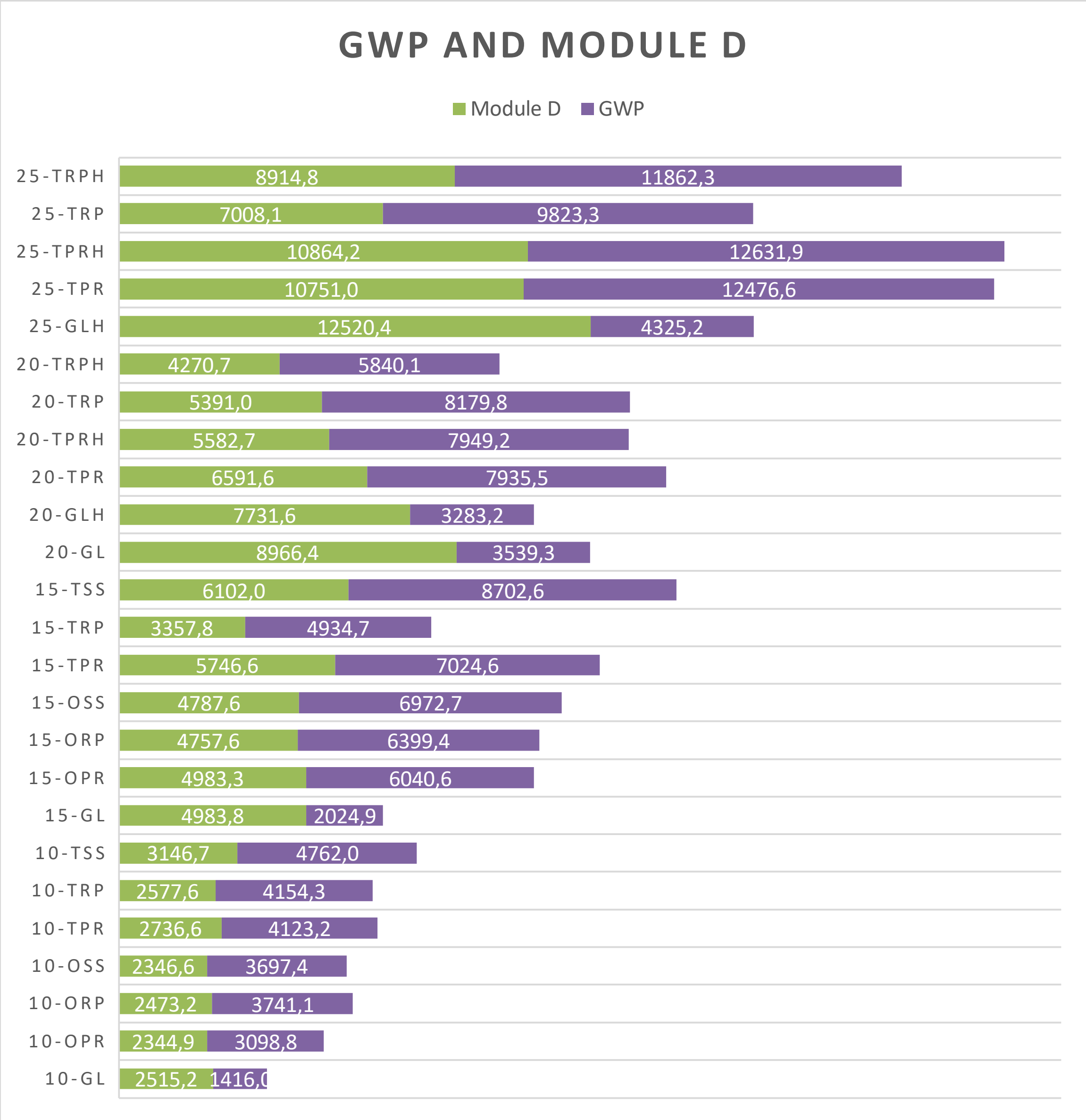

Figure 4-6 Total GWP if benefits were ignored and virgin materials were not treated in sustainable way.

The benefits in module D represent reduced release, binding, and storing of carbon emissions. For steel products part of benefits come from recycling of raw materials. Benefits of potential gain in future recycling is not presented, as the scope of LCA is 100 years. If benefits were non-existent, the total GWP would then be the combination of module D and the footprint as demonstrated in Figure 4-6.

4.2 GWP comparisons

In all spans, wood frames had lower GWP when compared to steel frames. Wood had also relatively higher weight compared to steel frames. The open profile steel frames with 10 m span had in average lower GWP then tube profiles in the same span length. Same can be seen in 15 m range. In longer spans, frames with trusses had big differences among their weight and GWP, see Figure 4-7.

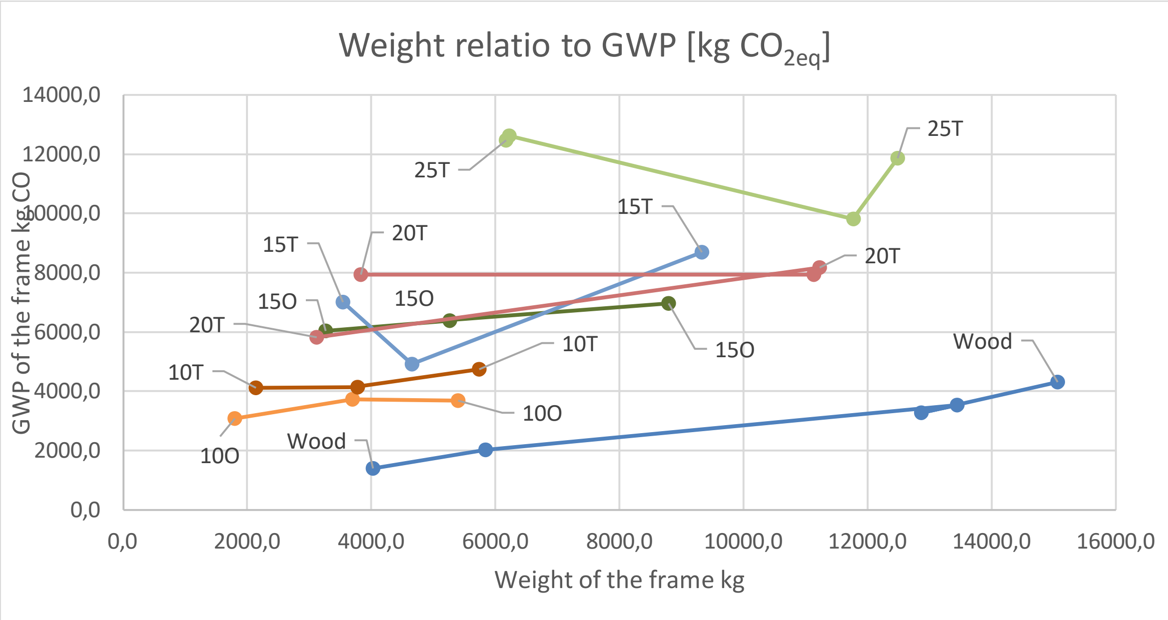

Figure 4-7 Weight compared to GWP, each line represents a span length and a profile type. The label in the end of the line informs the span length and the member type.

The first study question was related to how much a static model of a frame affects the frame total GWP. In this study, 10 m and 15 m span lengths were tested with two different member types and three different frame types, see Figure 4-8.

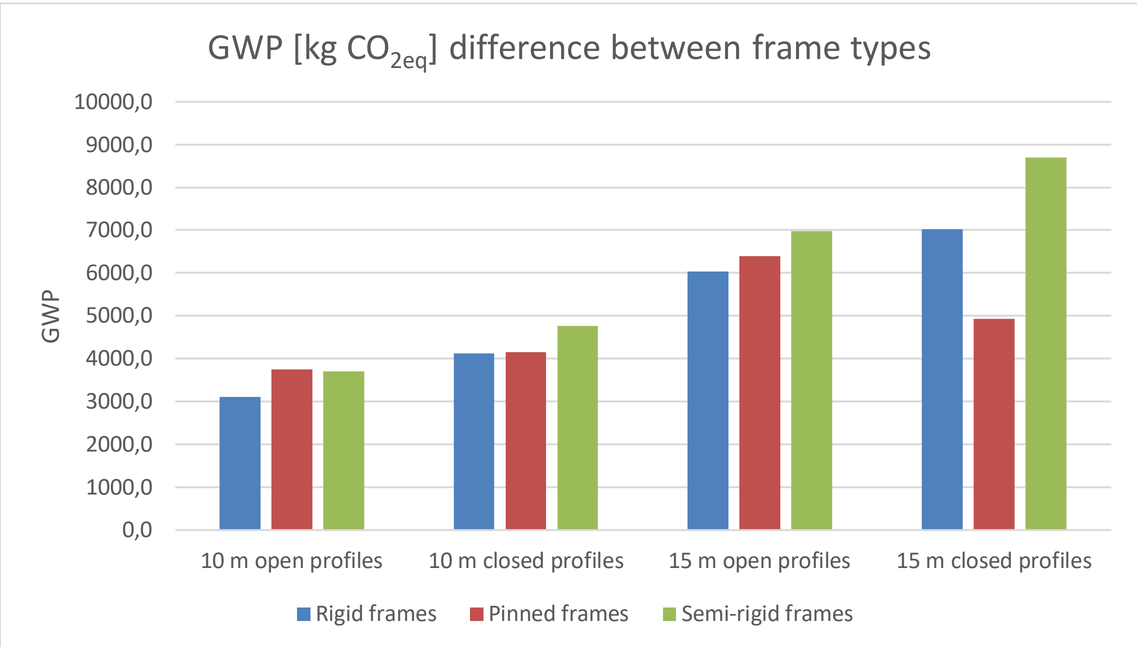

Figure 4-8 Comparison between frame types.

In the case of 15TRP, the single beam was replaced by a truss, to restrain the beam from deflecting too much. Due to having more height in the mid span, the efficiency caused exceptionally low weight for the case. On the other hand, if the requirements for the beam height was restricted, a standard sized profile could not have dealt with design requirements.

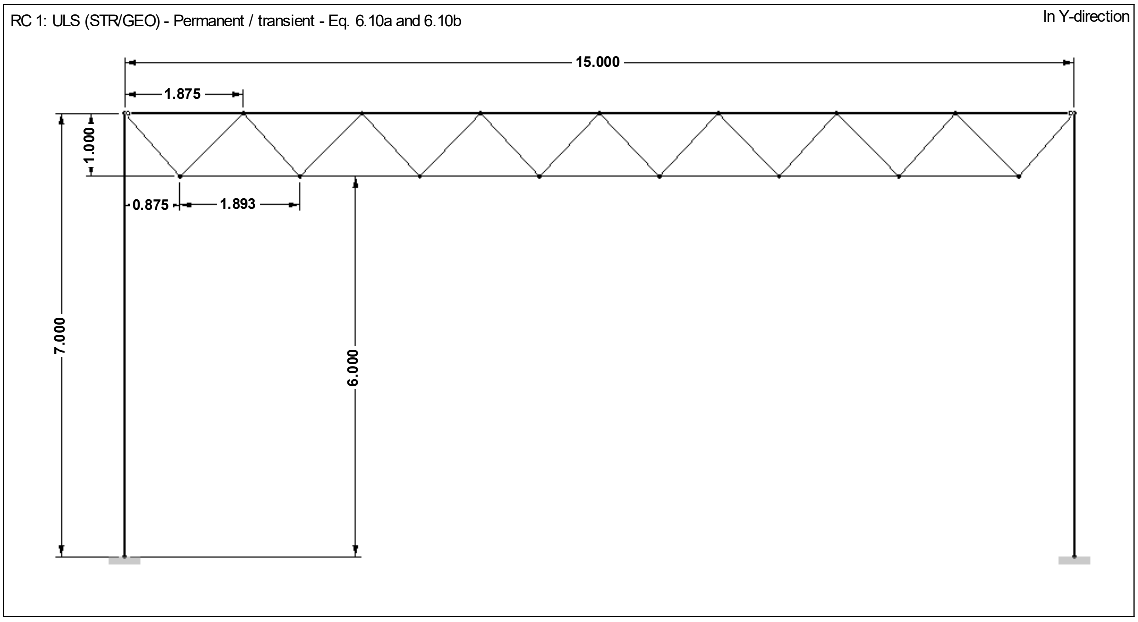

Figure 4-9. Frame 15TRP. 15 m truss made of tube profiles, rigid column base, pinned truss-to-column connection.

Second study question was related to how the higher strength of a frame compares to normal strength. In this study, open profiles were made of normal steel strength S355J2, while closed profiles from S420MH. Open profiles were made assumed to be hot rolled, while closed profiles cold-formed. Results indicate that open profiles performed better than closed profiles, even with strength advantage, see Figure 4-10. Except 15TRP which performed better, due to having a truss instead of a single beam.

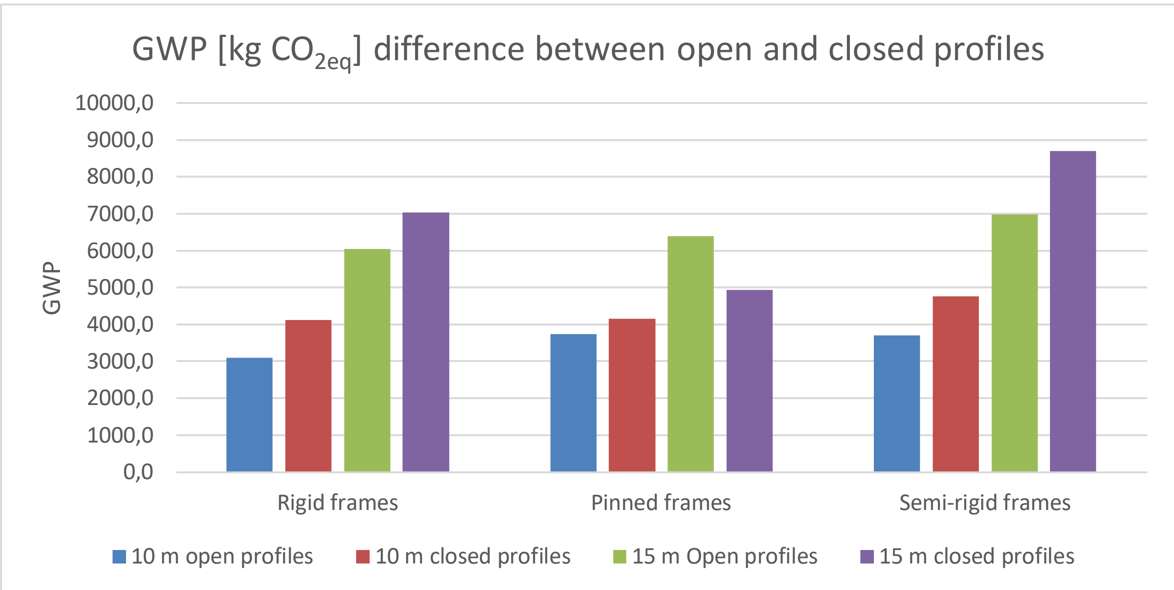

Figure 4-10 Comparison between open profiles and closed profiles

Third study question compared the total GWP between wood and steel frames. The comparison is done by comparing the contribution to a squared meter area, see Table 4-5. Wood frames did have smaller GWP than steel frames.

Table 4-5 Total GWP [kg CO_{2eq}/m^2] emissions of each component per square meter of net area. Value based on modules A1-A3 + C1-C4.

Name	Total	Frame	Footing	Plates	Welds
10-GL	23,5	10	3,67	4,97	1,63
10-OPR	51,5	42	1,13	3,92	1,92
10-ORP	62,3	47	3,67	7,14	1,38
10-OSS	61,5	45	6,36	4,96	1,70
10-TPR	68,7	53	1,13	11,44	1,13
10-TRP	69,1	51	3,67	9,99	2,06
10-TSS	79,3	60	6,36	8,19	1,20
15-GL	22,4	12	3,11	3,52	1,08
15-OPR	67,0	58	1,16	3,83	1,73
15-ORP	71,0	58	3,11	6,19	1,90
15-OSS	77,4	59	6,53	6,56	1,72
15-TPR	78,0	68	1,16	5,94	1,00
15-TRP	54,7	42	3,11	5,54	2,22
15-TSS	96,6	76	6,53	9,78	1,15
20-GL	29,4	16	6,52	2,73	0,81
20-GLH	27,3	14	6,52	2,68	0,81
20-TPR	66,0	58	0,87	4,18	1,51
20-TPRH	66,2	51	6,52	3,96	1,40
20-TRP	68,1	51	6,52	6,27	1,40
20-TRPH	48,6	40	0,87	5,91	0,90
25-GLH	28,8	17	5,22	2,19	1,02
25-TPR	83,1	75	1,17	4,15	1,58
25-TPRH	84,1	75	1,17	4,26	1,63
25-TRP	65,4	51	5,22	5,12	1,32
25-TRPH	79,0	64	5,22	5,63	1,34

Fourth study question was related to increase of GWP in longer spans. Wood frames did have a linear increase in GWP, see Table 4-6. While for steel frames, the increasing of span had no apparent increase or decrease of emissions per square meter, see Table 4-7.

Table 4-6 GWP [kg CO_{2eq}/m^2] emissions for wooden frames for each span.

Name	Total	Frame	Footing	Plates
10GL	23,5	14	3,67	4,61
15GL	22,4	17	3,11	4,65
20GL	29,4	23	6,52	5,15
20GLH	27,3	20	6,52	4,74
25GLH	28,8	25	5,22	5,97

Table 4-7 GWP [kg CO_{2eq}/m^2] emissions for rigid steel frames with pinned beam connections.

Name	Total	Frame	Footing	Plates
10TRP	69,1	51	3,67	11,29
15TRP	54,7	43	3,11	6,80
20TRP	68,1	51	6,52	7,54
20TRPH	48,6	39	0,87	7,52
25TRP	65,4	49	5,22	6,37
25TRPH	79,0	68	5,22	7,23

For wood frames the wood material itself was only responsible of 52 % of emissions in average, see Table 4-8. The plates and footing become greater emission sources due to relatively small GWP of the wood.

Table 4-8 Proportion of members per total GWP for steel and wood frames in average.

Steel frames/total	Wood frames/total
80 %	52 %

Wood did not achieve better strength compared to weight, especially in longer spans. Moreover, the connection parts contributed relatively more to wooden frames. Therefore, direct comparison of only members gives misleading results. Based on these results, steel frames had over two times more emissions compared to wood, see Table 4-9.

Table 4-9 Wood frame compared to steel frame per square meter.

	kg CO_2eq/m^2
Wood	26.3
Steel	69.9
Wood/Steel	38 %
Steel/Wood	266 %

Study question five questioned the relevance of module A4 and A5, especially when some of the materials are neglected in preliminary assessment. The relative share of connection components such as bolts, anchors, plates, reinforcements, and welds, for wooden frames made 24-33 % out of total GWP while for steel frames it made around 13 %. In average, connection in wooden frames produced 11.13 kg CO_{2eq}/m^2 and connection in steel frames produced 12.52 kg CO_{2eq}/m^2.

It should be noticed also, that modules A4 and A5 had smaller total GWP compared to modules A1-A3 + C1-C4. Transportation and installation made in average 1 % of emissions in the steel frames combined and 6 % for wood frames.

Sixth study question was related to comparison of components. Figure 4-11 and Figure 4-12 show a pie chart of relative distribution of source by component. For wood frames the member itself made approximately half of the GWP. In direct comparison between wood and steel, steel had about five times higher GWP. However, when relevant components such as footing, reinforcements and fasteners of the frame are included, the steel had only a bit over two times higher GWP. Assembly when wood had the same design life as steel. In any other case, GWP would be approximately the same. Figure 4-11 and Figure 4-12 demonstrates the GWP contribution of each component in the frames on average.

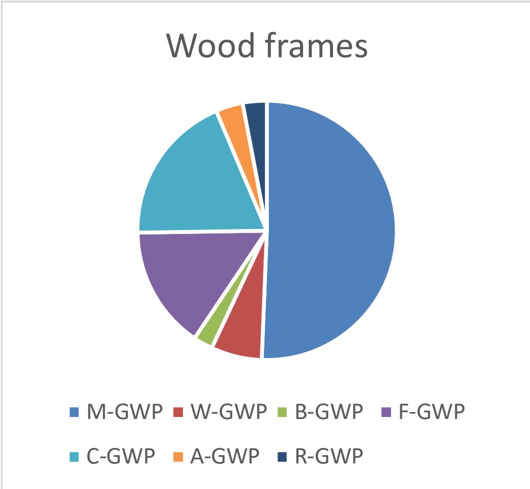

Figure 4-11 Comparison of average GWP sources in the wooden frames of 10 m and 15 m spans.

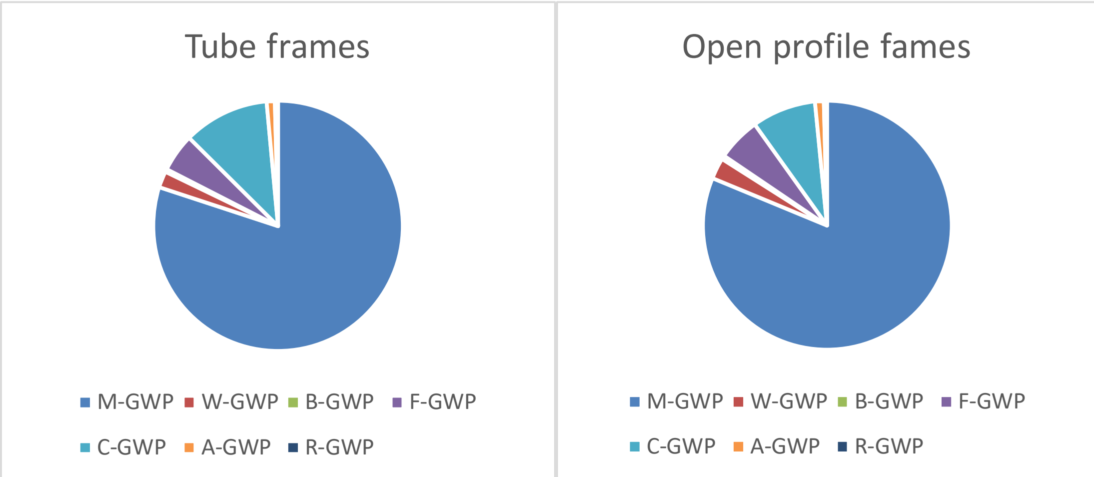

Figure 4-12 Comparison of average GWP sources of steel frames of 10 m and 15 m spans.

Where	M	Members
	W	Welds
	B	Bolts
	F	Footings
	C	Connection plates
	R	Reinforcements
	A	Anchoring bolts

5 Conclusions and future work

This study has identified how static models of steel frames influence design of frame members and therefore also the total GWP emissions. The aim was to fill the gap for embodied carbon emissions of a streel frame. The frame models produced results which could be analyzed to improve the low carbon design of structures.

5.1 Conclusions

The analysis consisted of pinned, rigid, and semi-rigid frames. In total, 25 frames were modelled to improve reliability of results. Frames were designed in Dubal RFEM and detailed modeling was done in Tekla Structures 2018 to generate material lists for each member and component. The carbon footprint of each frame was calculated as a sum of its components. GWP factors were gathered from European EPD-reports. Beside embodied carbon emissions, assessment included relevant GWP sources coming from welding fumes and energy consumption in transportation and installation. The wooden frames were modeled with pinned beam connections and mast columns, to work as reference for steel frames.

The results verified the relevance of frame type to GWP emissions. Results also indicated the significance of member type, material strength and importance of including connecting components in assessment. For the studied frames, pinned frames performed better than rigid or semi-rigid frames. Whereas semi-rigid frames against expectations performed worse than the other two frame types. The semi-rigid connections in modeled frames, did not necessarily reduce the utilization ratio of a member enough, to allow the use of a smaller member. Moreover, unlike the other two frame types the semi-rigid frames transferred the moment from the beam to the foundations, which increased the size of footings and increasing the total GWP.

Hot rolled open profiles and cold-formed tube profiles were modelled in 10 m and 15 m span lengths. Hot rolled open profiles were made of 355 MPa steel while tubes from higher steel strength of 420 MPa. High strength steel could not outperform IPE or HEA profiles in terms of carbon emissions for the studied frames. It seems that the optimal geometry outweighed the material properties.

Connections in the studied frames were responsible for 13-33 % of total GWP emissions. Carbon sources came from connecting plates, bolts, reinforcements, welding fumes and welding wires. Whereas transportation and installation were responsible of 1-6 % of emissions combined. Based on the analysis, the 10 m span in the studied wooden frame had 50 % of emissions coming from member materials. Findings indicate that including connecting components is significantly importnat especially in wooden frames.

5.2 Discussion

For the studied steel frames, pinned frames performed the best. Horizontal loads were mainly wind-load, which allowed to use relatively small columns. Semi-rigid frames performed the worst, possibly due to the fact, that columns had to withstand the wind load and transferred bending moment coming from the beam. Footing in these cases was also the biggest, due to fact of having greatest moment in the connection.

In Nordic countries, hot rolled open profiles are made of normal streel strength of 355 MPa. Whereas tube profiles can be made of higher steel strength. Higher steel strength is supposed to lower material usage, and embodied carbon emissions. However, hot rolled open profile outperformed higher steel strength due to having more optimal geometry to resist bending moment.

Operation time for both wood and steel frames were assumed to be the same. However, steel structures have often surpassed their designed life expectancy. Whereas wood structures usually have shorter life expectancy of 30-50 years compared to steels 100 years. Nevertheless, wood industry promises in their new products 100-year life expectancy, therefore the comparison in this study excluded replacement of wood materials during the operation time as required in module B3 or B4. In this scenario wood performed better than steel. But even one replacing would undo the benefit.

This thesis contributes to the gap for lack of comparison of different steel frames based on static model and member types. Analysis is restricted to initial carbon emissions of one level frame types. The results and comparison verified claims regarding the low carbon design. However, this study only consisted of 25 frames with different type of members and connections. More reliable study would require bigger sample size.

5.3 For future work

The analysis compared open steel profiles to tube profiles. Open profiles performed well in comparison, even with lower steel strength. Therefore, considering cold-formed open profiles could be a valid way to lower GWP of a steel structure.

Weight of the wooden frames increases rapidly in over 15 m long span. However, wood beams can be reinforced with steel. Steel is great at dealing with tensile stress, combining the two materials with wood for compression and steel for tension could reach lower GWP than having two materials working separately.

Foundations of frames in this study were detached footings. However, foundation can be made of different options such as wall footing or pile foundation. Comparing the benefit of each foundation type could help in design of low carbon structures.

Multistory buildings require separate study to determine how material or frame type options influence the total GWP. A larger statistical study could fill a gap of information related to GWP of multistory buildings.

Statistically a single frame is not adequate to give valid result, but modeling several frames outlined the key components of the sources of embodied carbon. The accurate study would require greater data. Data could be collected from LEED or BREEAM database to ensure reliability of results. However, finding comparable materials remains a challenge, as most structures usually have unique loading and spacing in them.

The other problem related to comparison of wood and steel frames is related to design life and spacing of the frames. If wood structures have shorted life span, then their benefits are also smaller, as the embodied carbon is divided to the operational years. Secondly, requirements of the frames can change between different materials.

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Design standards

Eurocodes:

EN 1990-1-1 Basics of structural design

EN 1991-1-1 Actions on structures: General actions, self-weight, and imposed loads

EN 1991-1-3 Actions on structures: Snow load

EN 1991-1-4 Actions on structures: Wind load

EN 1993-1-1 Design of steel structures: General rules and rules for buildings

EN 1993-1-8 Design of steel structures: Design of joints

EN 1995-1-1 Design of timber structures: General rules and rules for buildings

EN 15978 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method

EN 15804. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products

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Appendices

APPENDIX A

Joining time of bolts

Regression for fastening time of beams to columns.

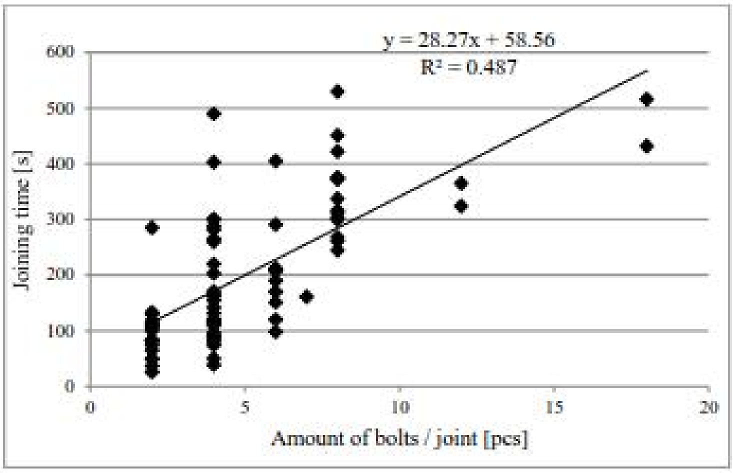


Fig. 43. Joining time of six different joint types (Knuuttila, 2011).

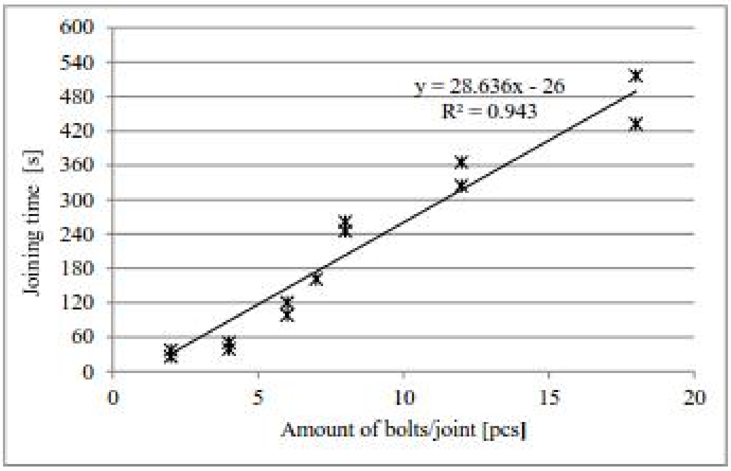


Fig. 44. Two minimum measured time values per amount of bolts in joint (Knuuttila, 2011).

Knuuttila came up with the following function:

$T_{Ej} = 30 \times n_{bi} - 26$ [s]

which can be presented as

$T_{Ej} = 0.5 \times n_{bi} - 0.42$ [min]

Figure 0-1 Haapio, 2012, p. 68

APPENDIX B

Welding time

Regression for welding time.

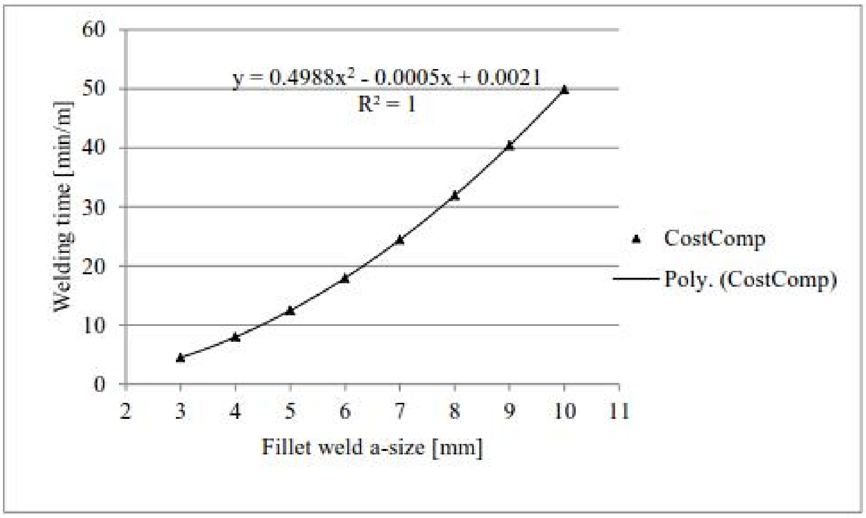


Figure 0-2 Haapio, 2012, p. 55

APPENDIX C

The geometry of all the frames

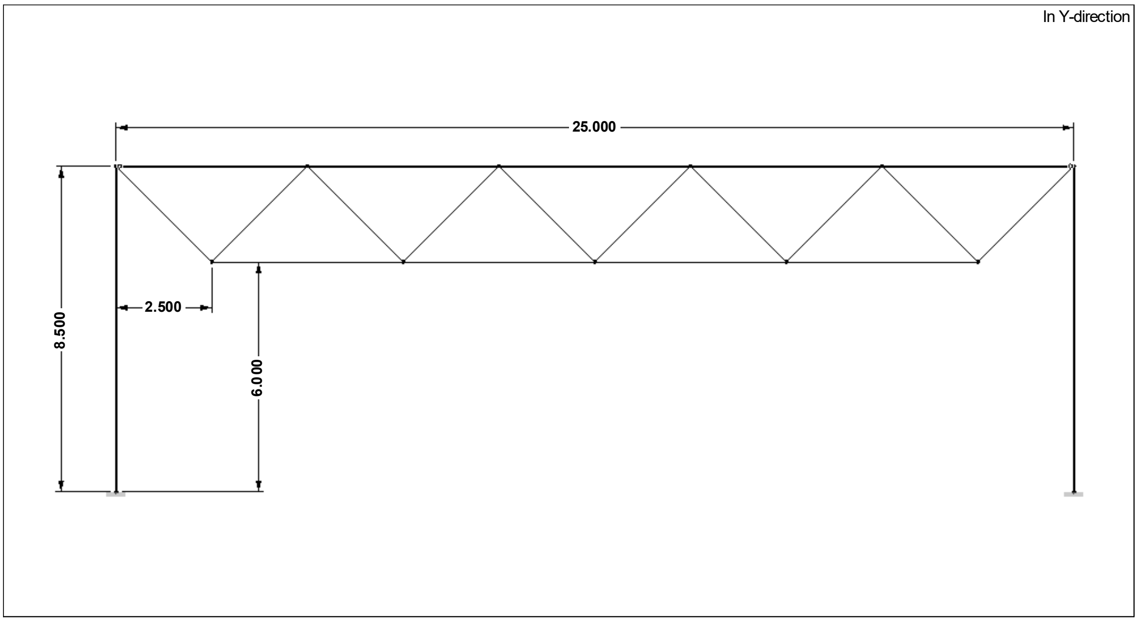


Figure 0-3 25 m span, rigid column base connection, pinned truss-to-column connection (25TRP)

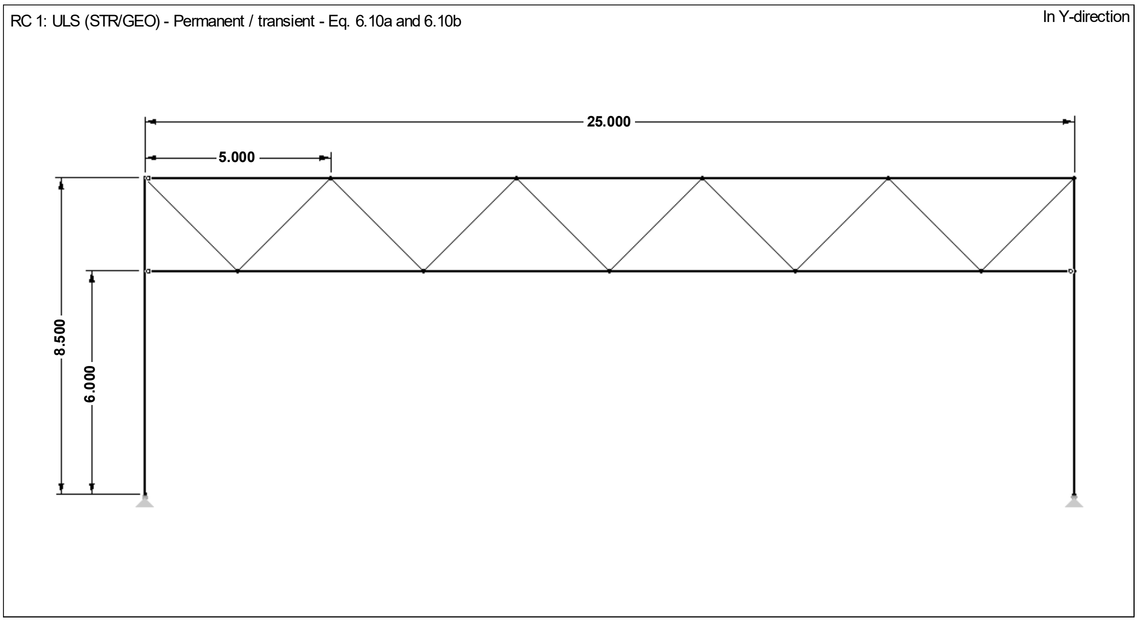


Figure 0-4 25 m span, pinned column base connection, rigid truss-to-column connection (25TPR)

APPENDIX C

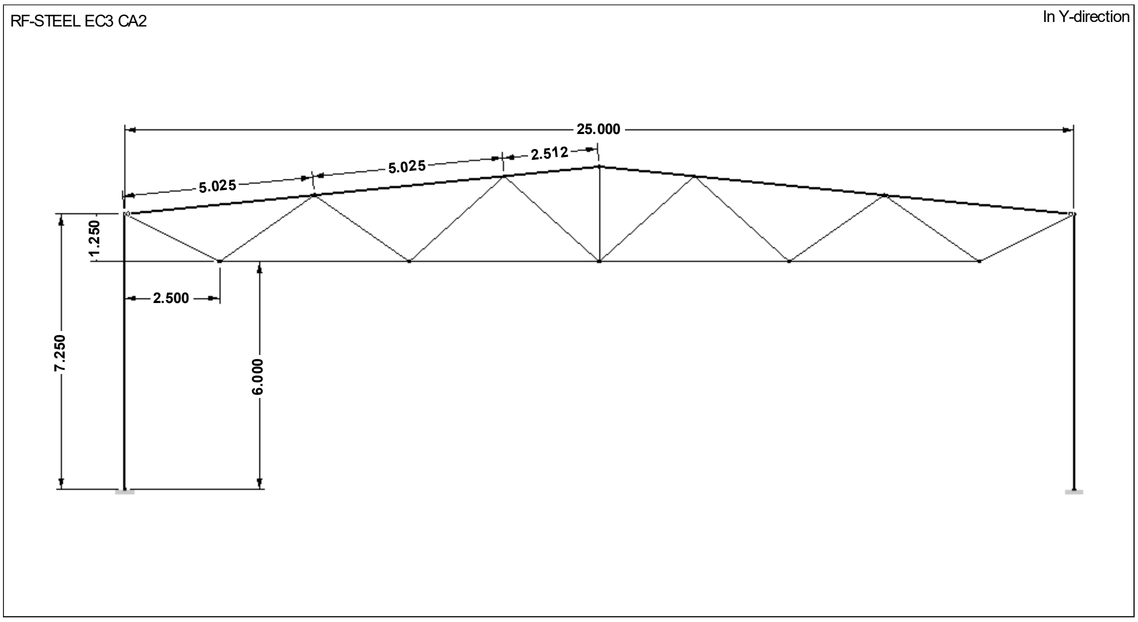


Figure 0-5 25 m span, pinned base connection, rigid truss-to-column connection, ridge in the middle (25TRPH)

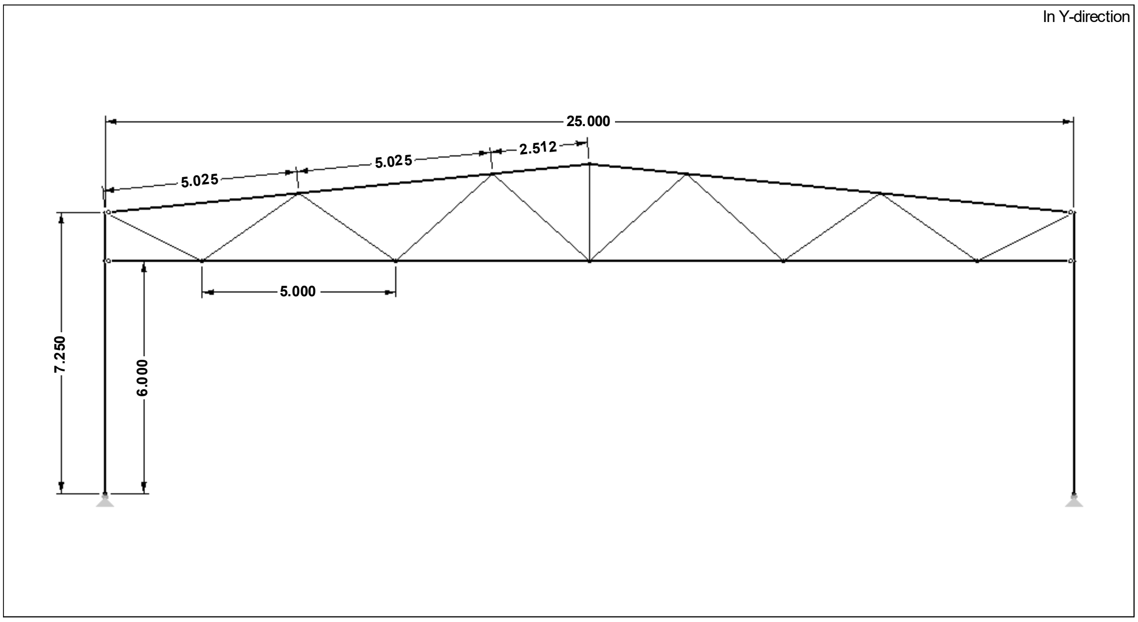


Figure 0-6 25 m span, pinned base connection, rigid truss-to-column connection, ridge in the middle (25TPRH)

APPENDIX C

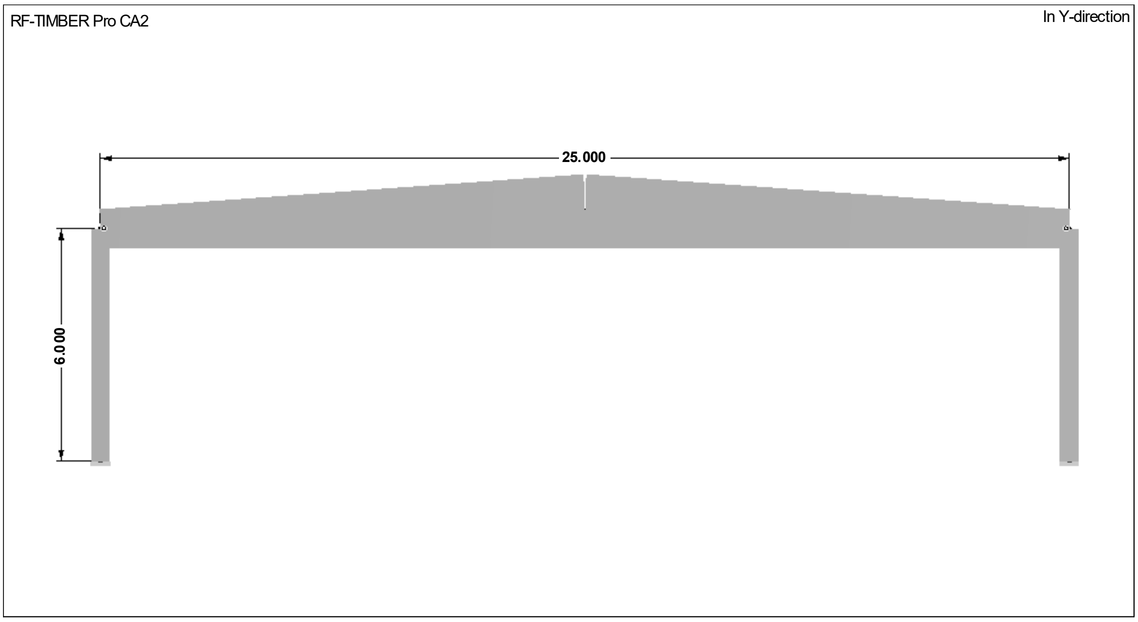


Figure 0-7 25 m span, wood frame, rigid base connection, pinned beam to column connection, ridge in the middle (GL25H)

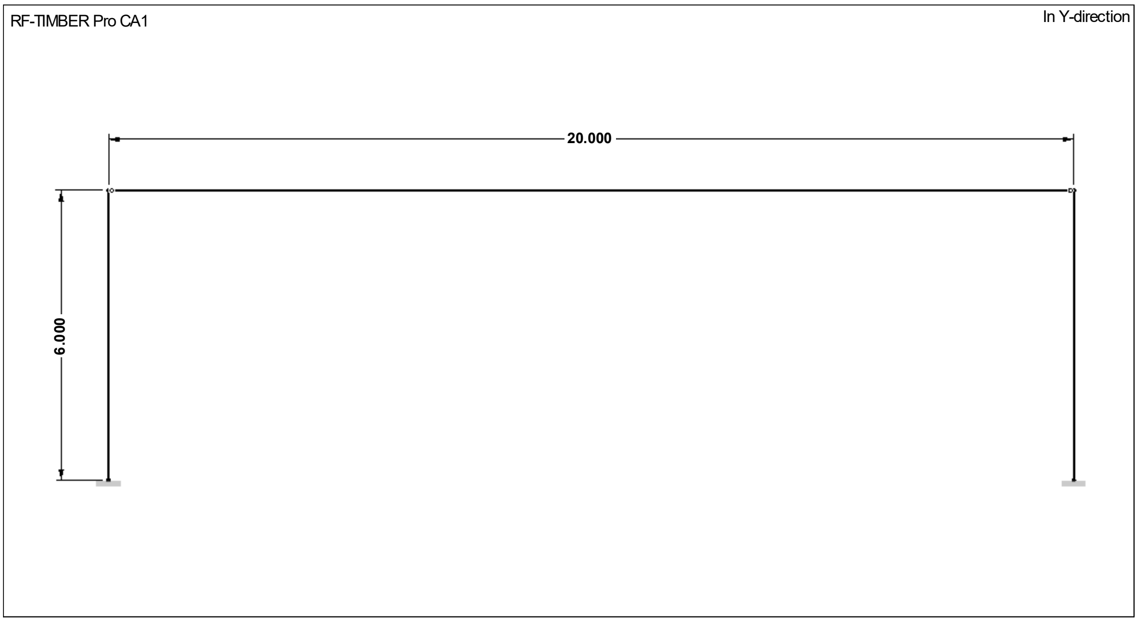


Figure 0-8 20 m span, wood frame, rigid base connection, pinned beam to column connection (GL20 and GL20H)

APPENDIX C

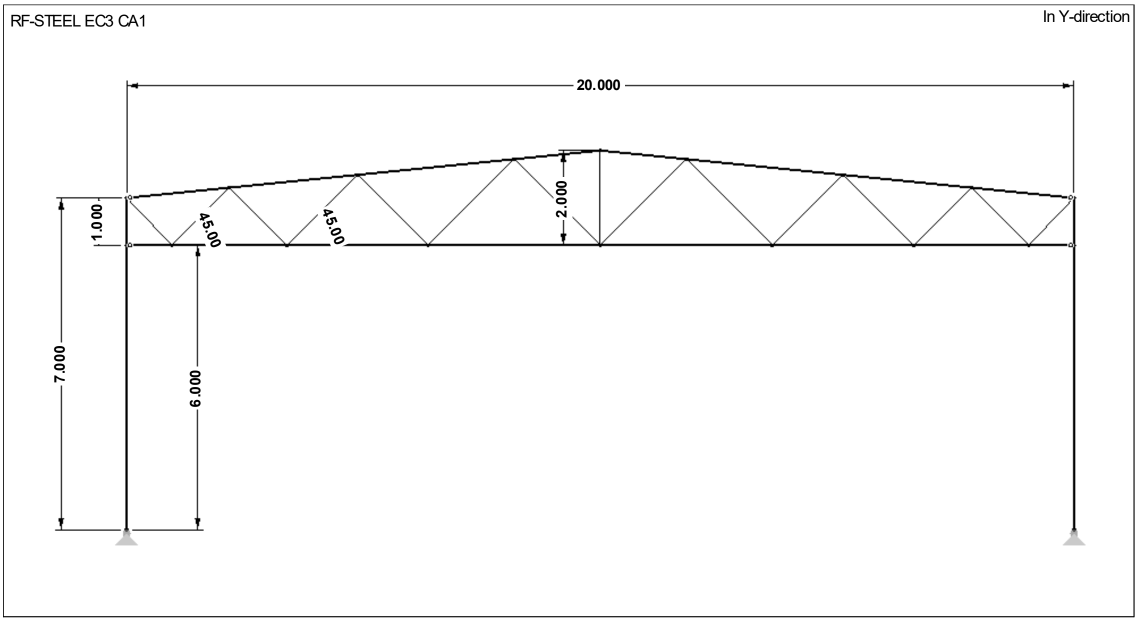


Figure 0-9 20 m span, pinned base connection, rigid truss-to-column connection, ridge in the middle (20TPRH)

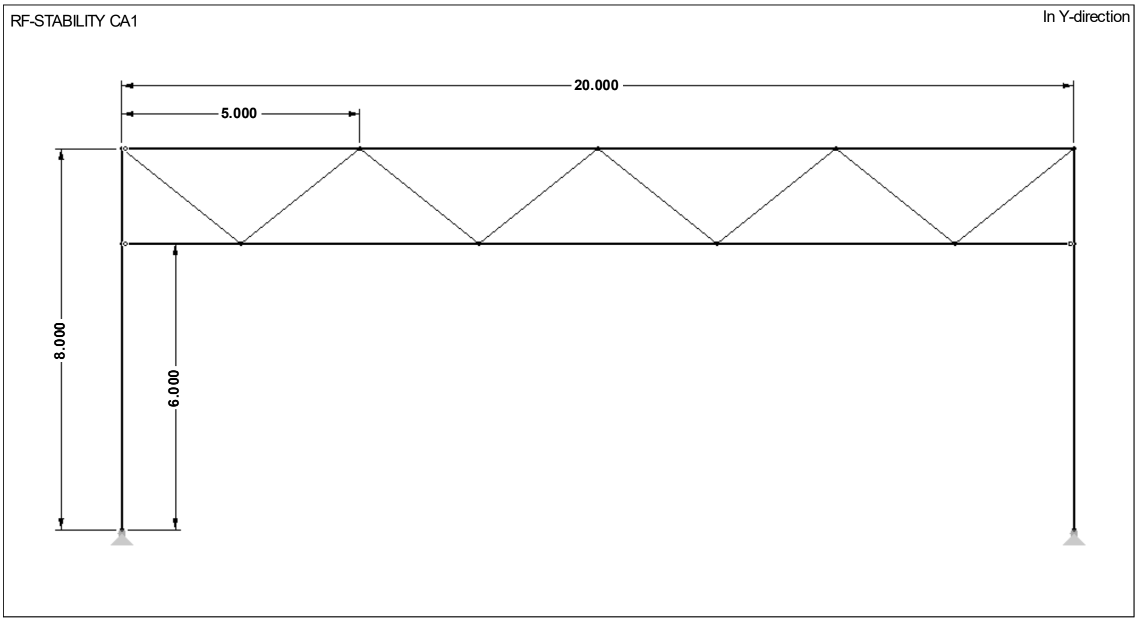


Figure 0-10 20 m span, pinned base connection, rigid truss-to-column connection (20TPR)

APPENDIX C

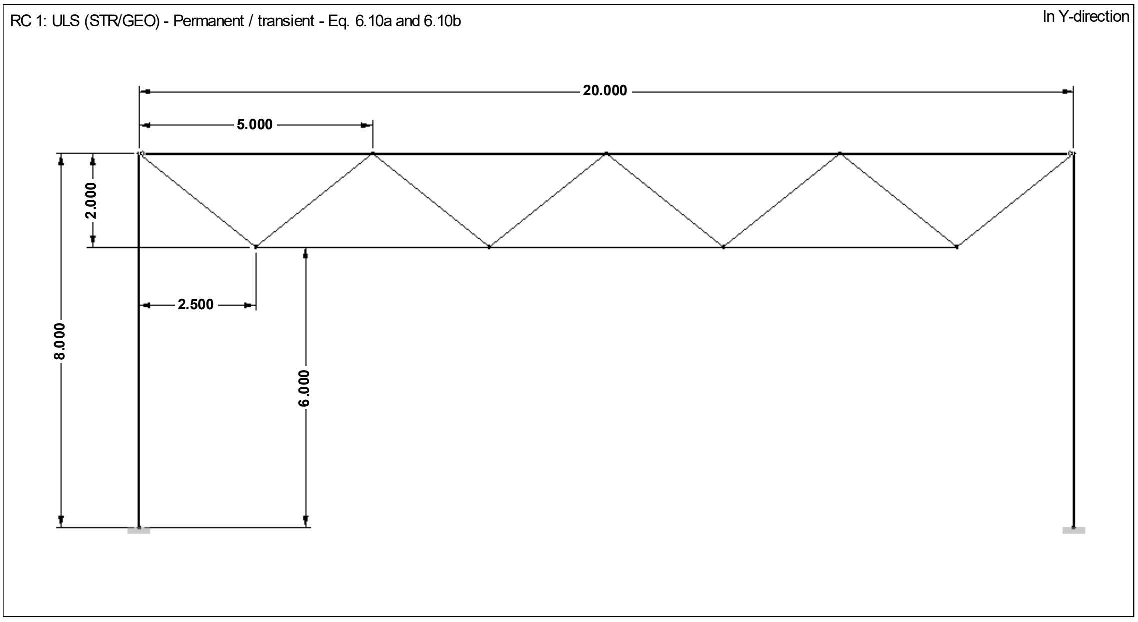


Figure 0-11 20 m span, rigid base connection, pinned truss-to-column connection (20TRP)

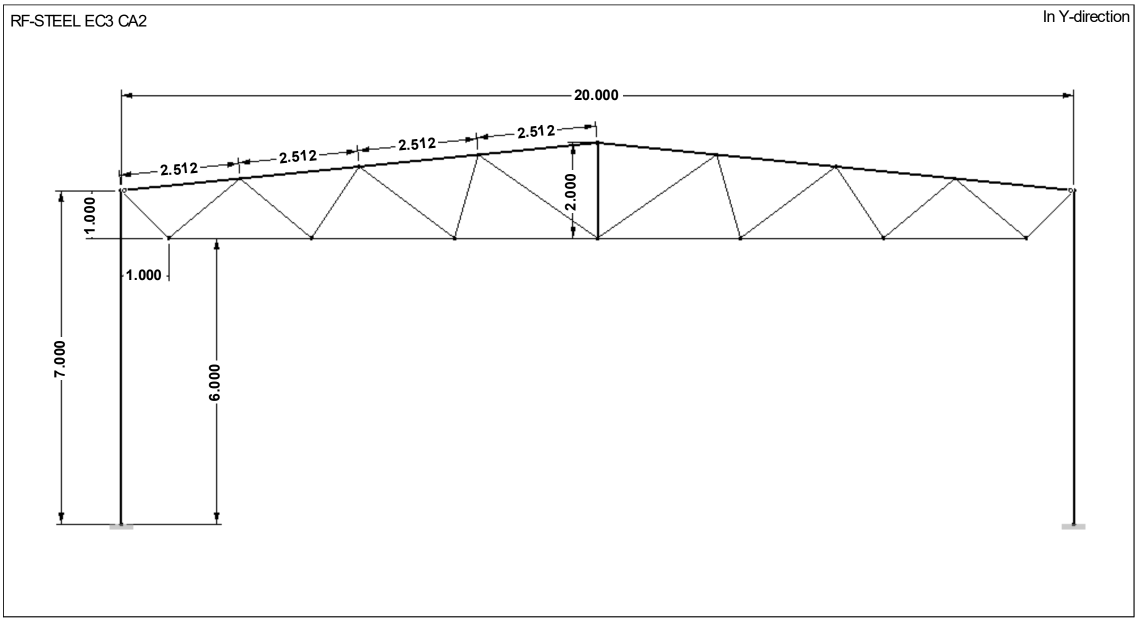


Figure 0-12 20 m span, rigid base connection, pinned truss-to-column connection, ridge in the middle (20TRPH)

APPENDIX C

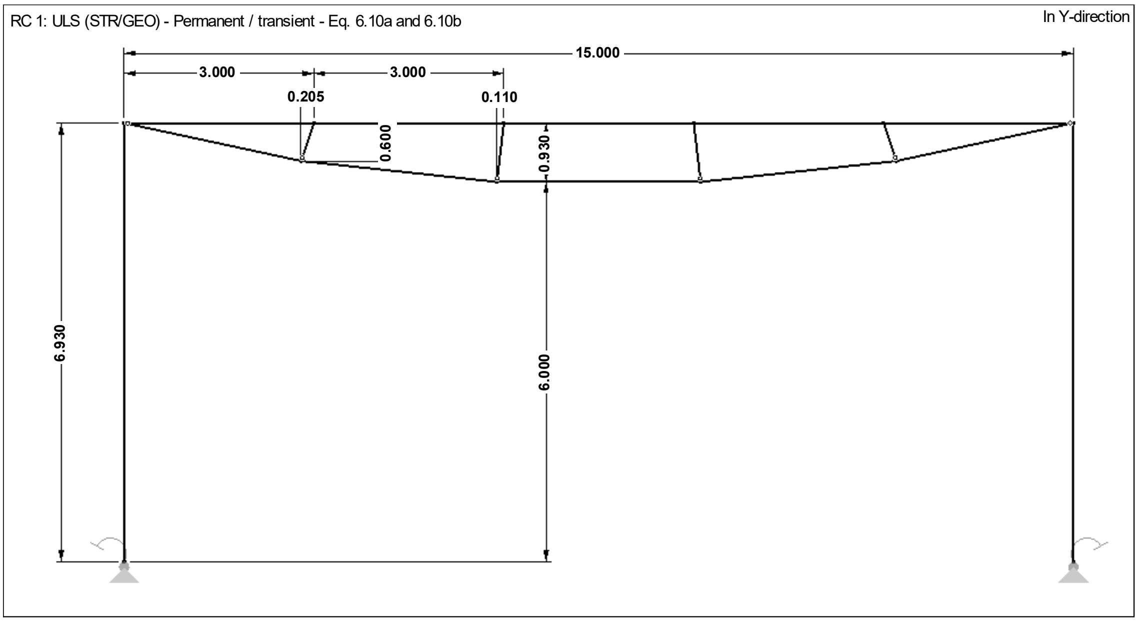


Figure 0-13 15 m span, pinned base connection, rigid beam to column connection, tension rod beneath the beam (15TSS)

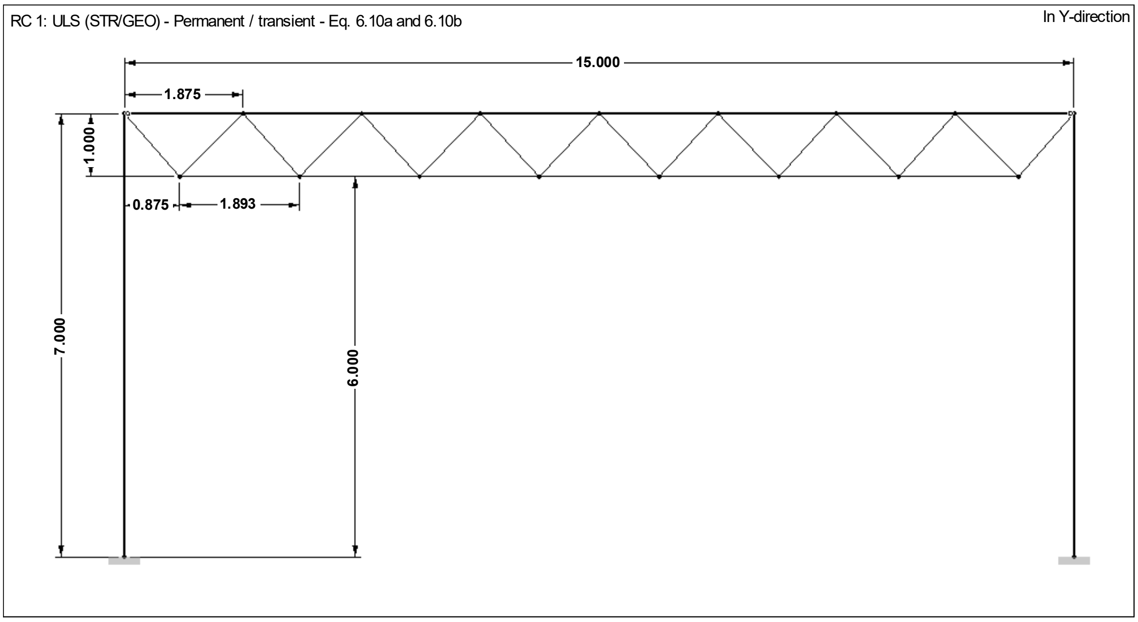


Figure 0-14 15 m span, rigid base connection, pinned truss to column connection (15TRP)

APPENDIX C

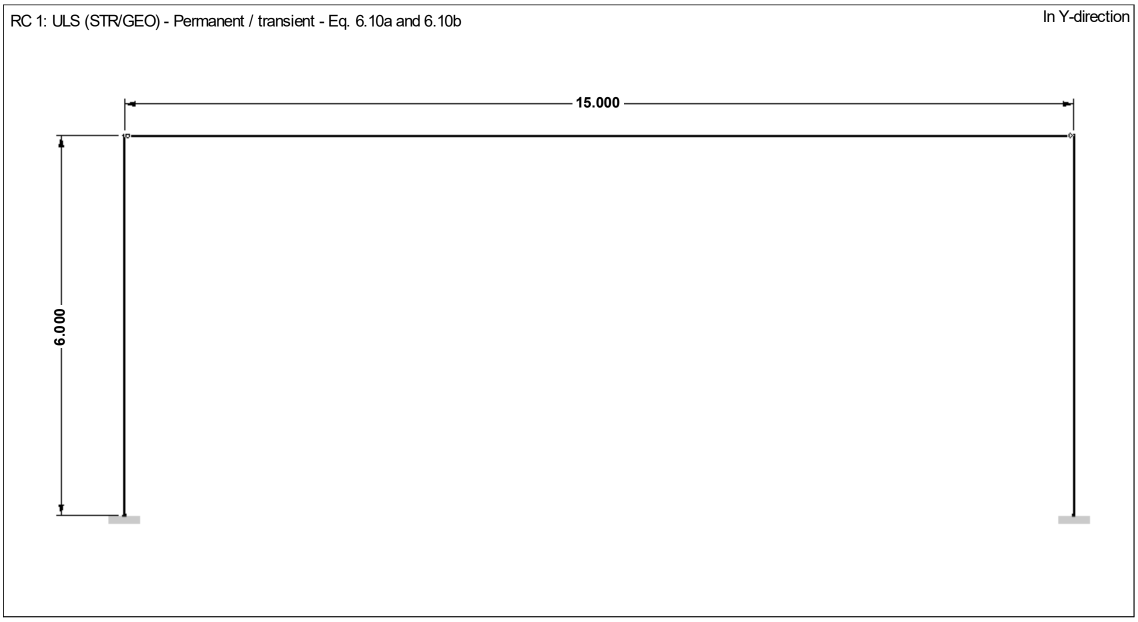


Figure 0-15 15 m span, rigid base connection, pinned beam to column connection (15GL, 15ORP). Same geometry used for (15TPR, 15OPR, 15OSS)

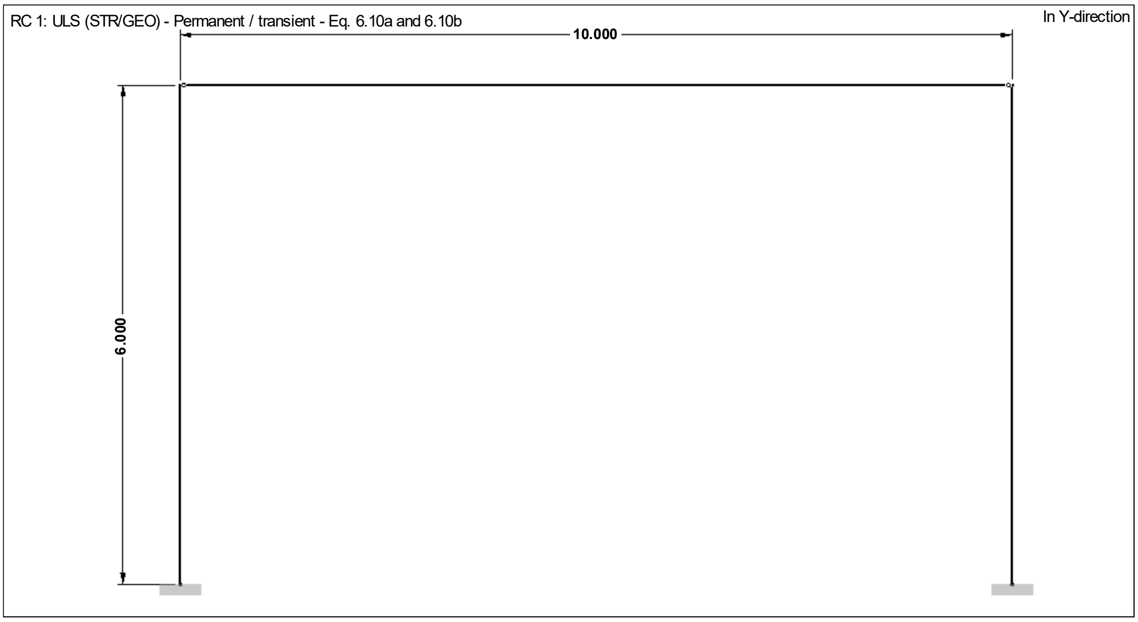


Figure 0-16 10 m span, rigid base connection, pinned beam to column connection (10GL, 10TRP, 10ORP). Same geometry used for (10TPR, 10OPR, 10TSS, 10OSS)

APPENDIX D

Optimization of trusses

This appendix shows screenshots taken from Dubal RFEM 5.20. It presents an example the design of frame of 15TRP. Figure 0-17 and Figure 0-18 show the loading of frames.

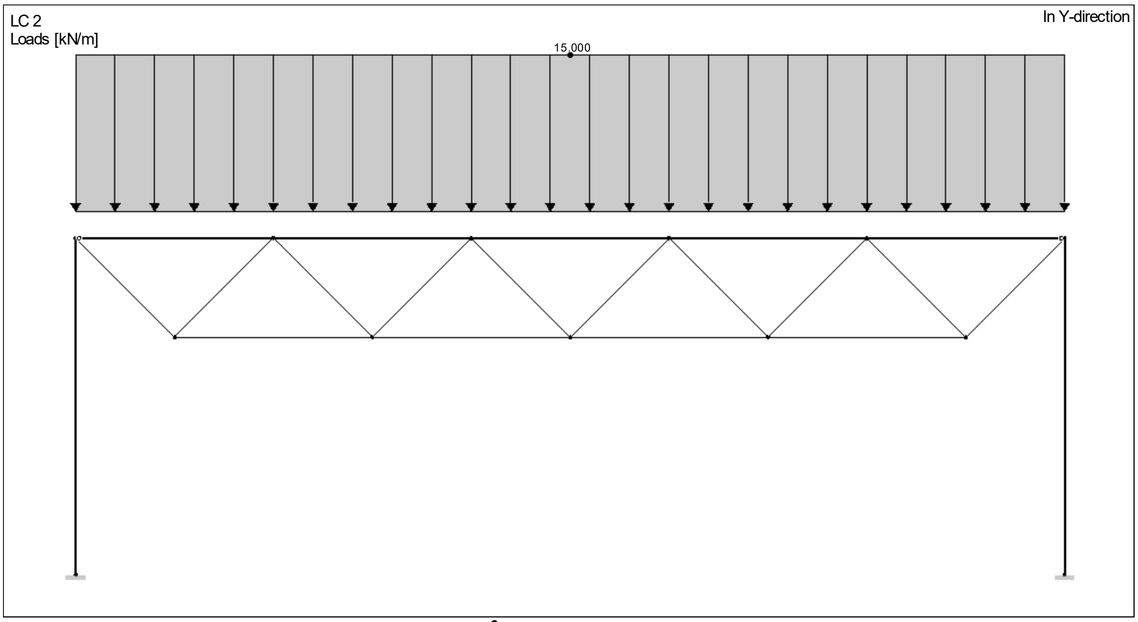


Figure 0-17 Applied snow load of 2.5 kN/m^2 with 6 m spacing results in 15 kN/m line load.

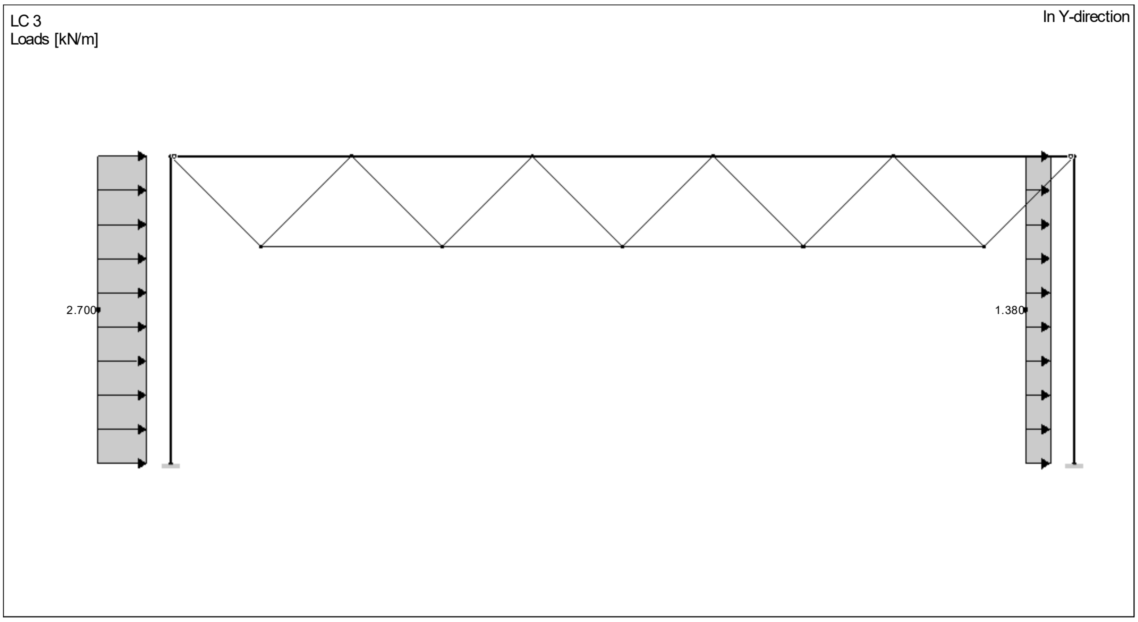


Figure 0-18 Applied wind load according to Eurocodes. Overpressure and under pressure considered. On the left wind load in D area and on the right wind load in area E.

The stresses in members can be seen in Figure 0-19, Figure 0-20, and Figure 0-21.

APPENDIX D

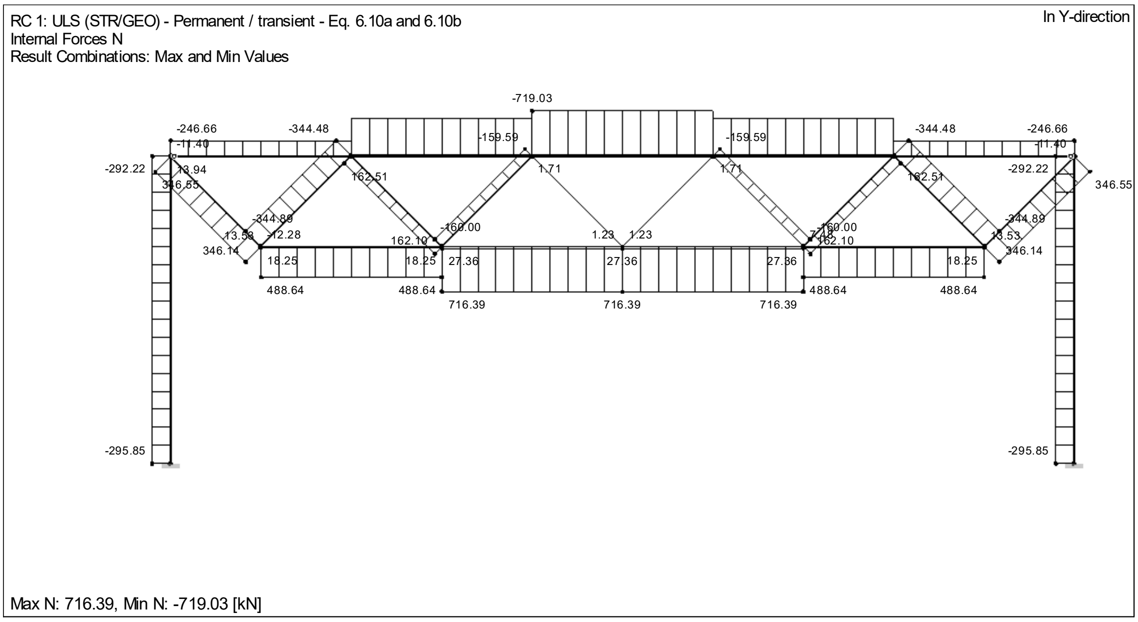


Figure 0-19 Normal forces of all members.

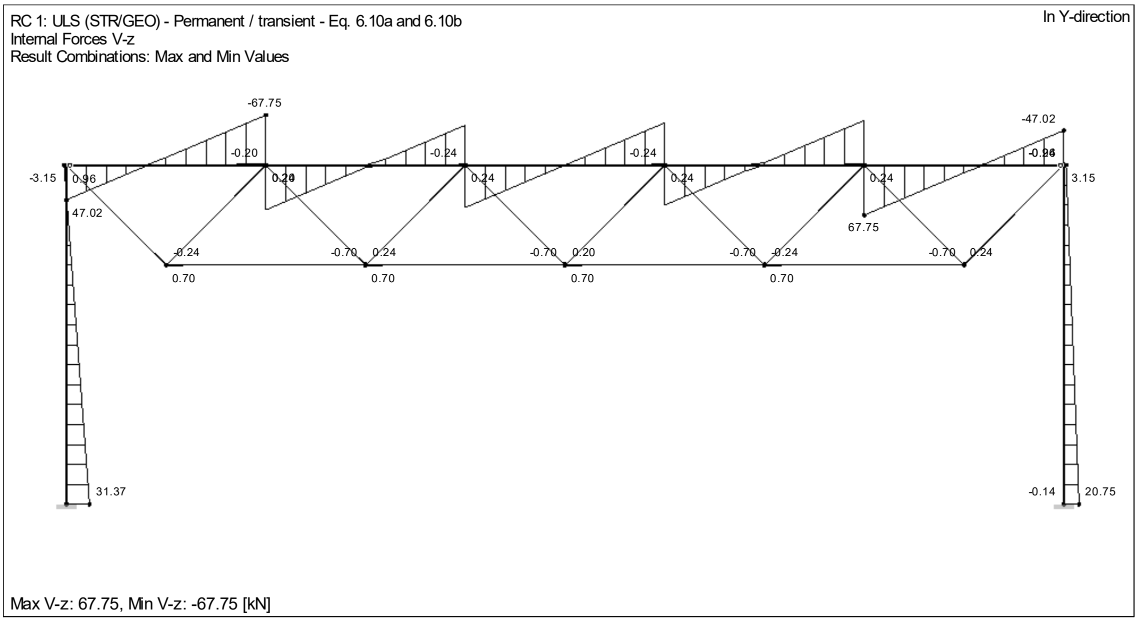


Figure 0-20 Shear forces of a top chord and columns.

APPENDIX D

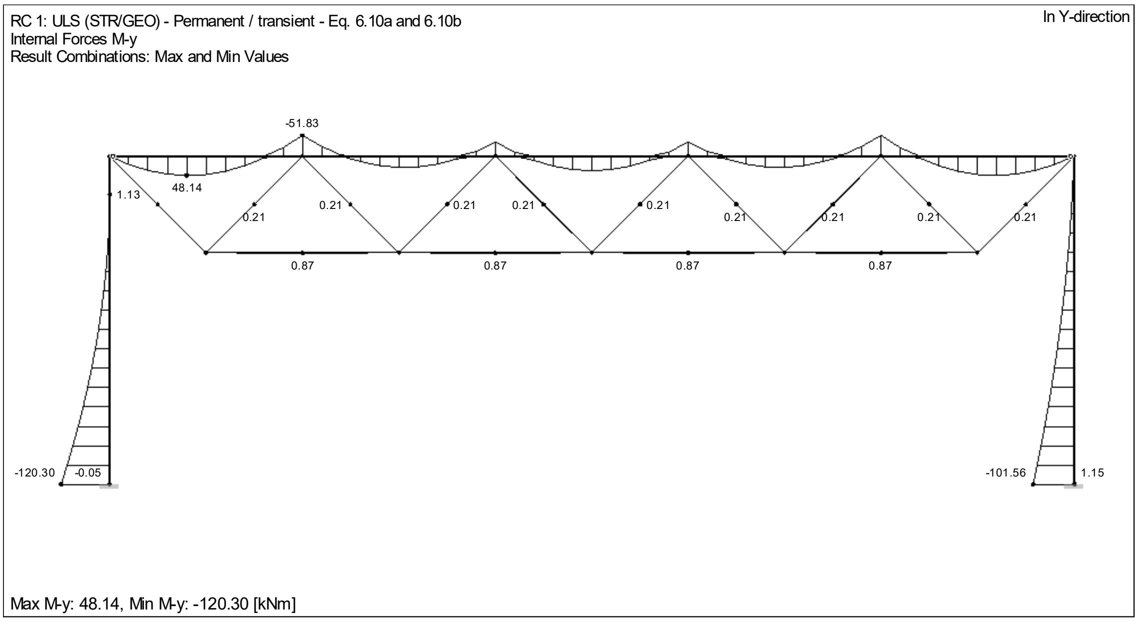


Figure 0-21 Moment of a top chord and columns.

The buckling of top chord was solved in on plane direction, see Figure 0-22, the effective length can be seen in Figure 0-23.

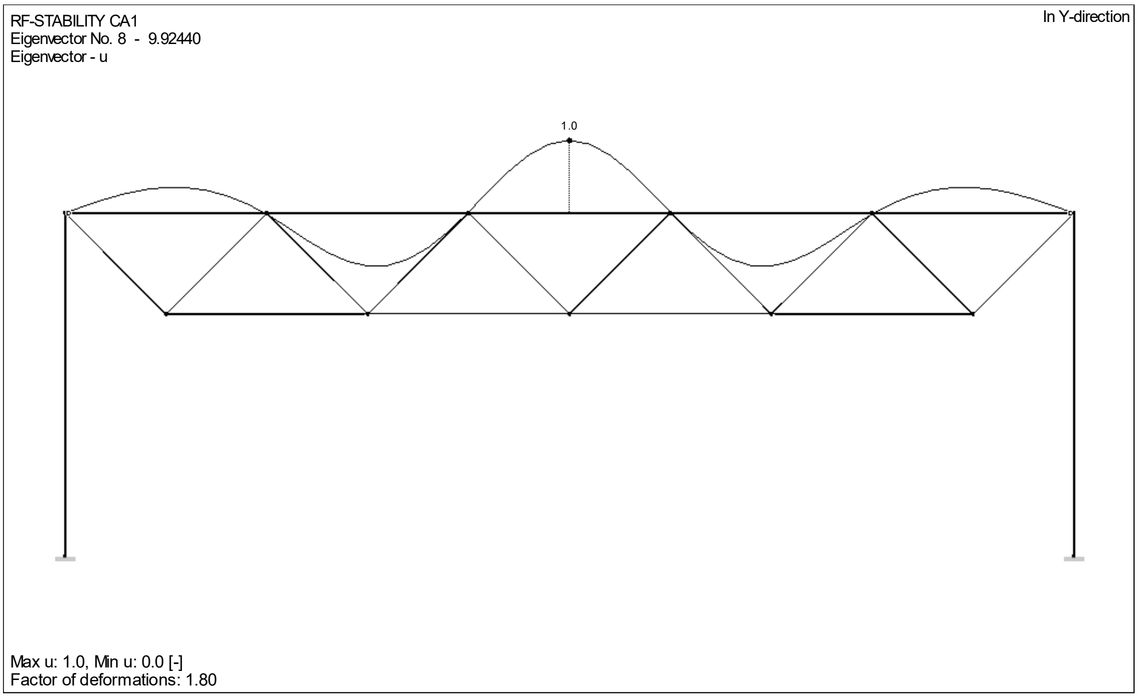


Figure 0-22 Example of buckling mode of the upper chord.

APPENDIX D

Member	Node No.		Length	E-vector	Effective Length [m]		Effective Length Factor [-]		Critical Load
No.	Start	End	L [m]	No.	$L_{cr,y}$	$L_{cr,z}$	$k_{cr,y}$	$k_{cr,z}$	N_{cr} [kN]
52	3	6	25,000	1	19,037	14,361	0,761	0,574	277,719
				2	10,326	7,790	0,413	0,312	943,895
				3	10,326	7,790	0,413	0,312	943,895
				4	7,027	5,301	0,281	0,212	2038,200
				5	7,027	5,301	0,281	0,212	2038,200
				6	6,684	5,042	0,267	0,202	2252,570
				7	6,380	4,813	0,255	0,193	2472,320
				8	5,382	4,060	0,215	0,162	3475,120
				9	5,237	3,951	0,209	0,158	3669,310
				10	5,237	3,951	0,209	0,158	3669,310

Figure 0-23 Effective length of the upper chord members in the mode, where buckling happened.

Design check was done for all the members in RFEM's calculation EN3 module. The utilization ratios of members is shown in Figure 0-24, Figure 0-25, Figure 0-26, Figure 0-27, and Figure 0-28.

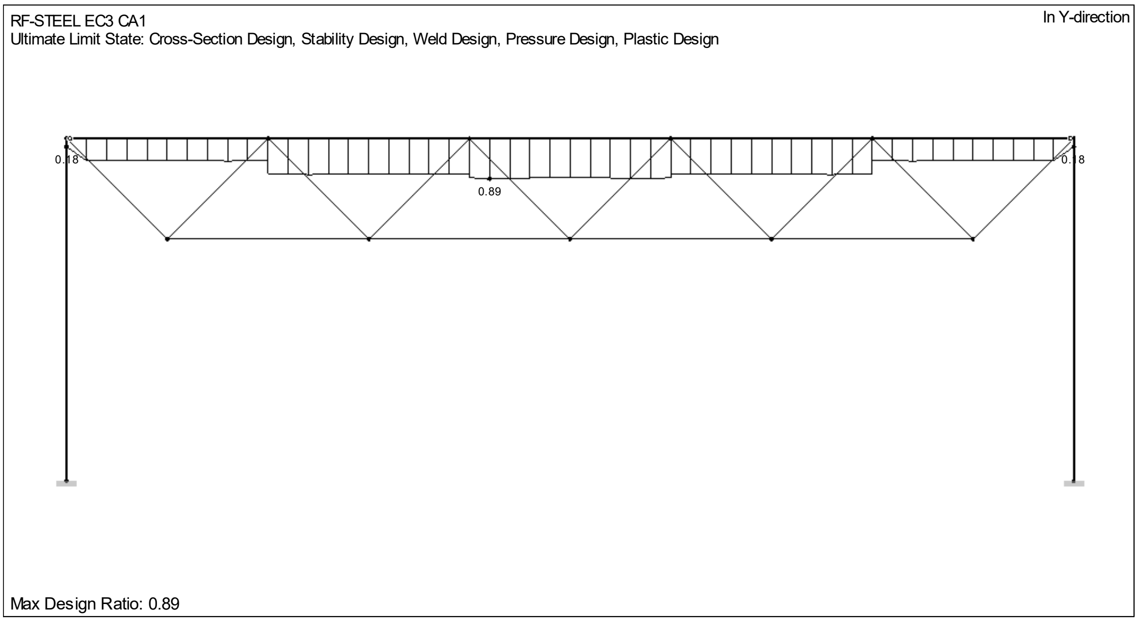


Figure 0-24 Verification of upper chord according to Eurocode 3, utilization ratio at 0.89.

APPENDIX D

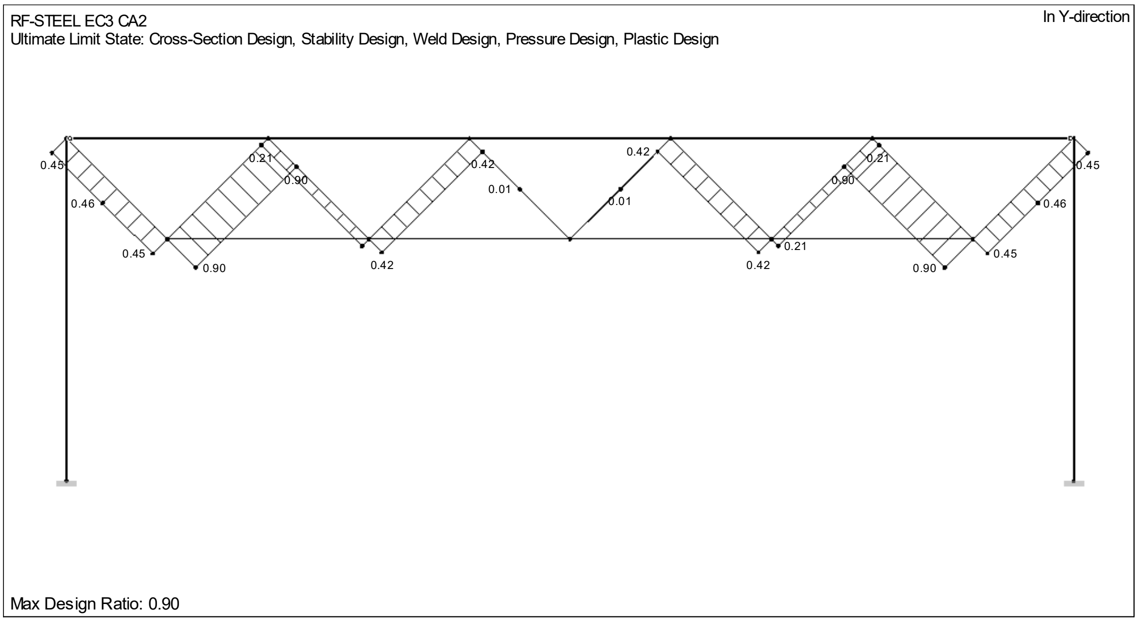


Figure 0-25 Optimization of trusses members according to Eurocode 3, utilization ratio at 0.90.

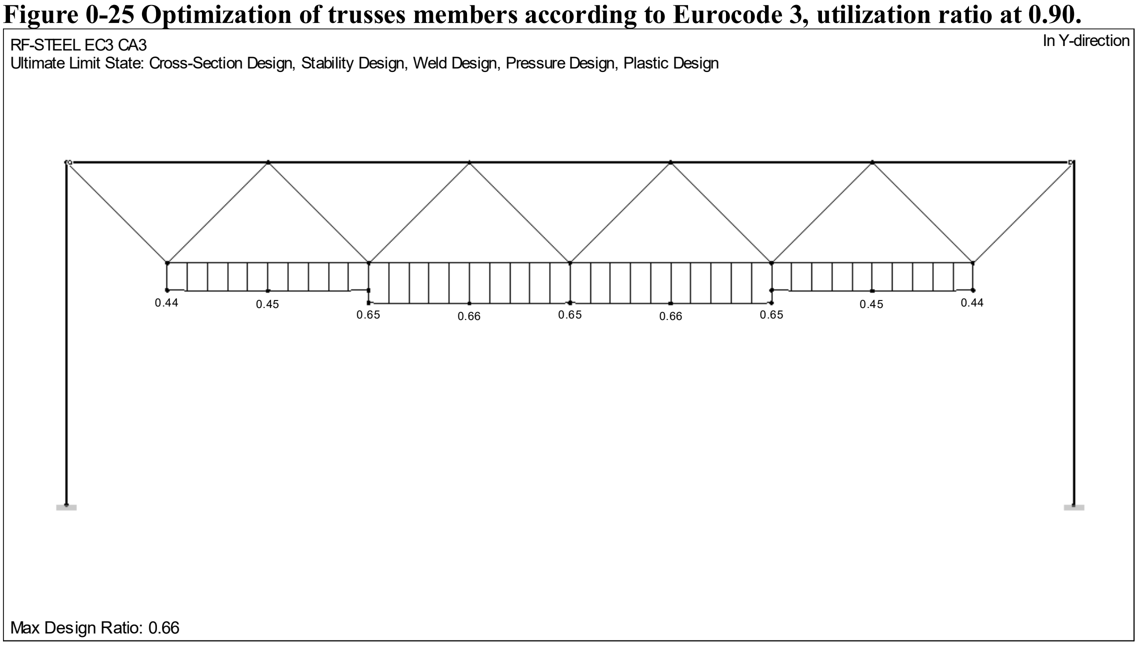


Figure 0-26 Optimization of bottom chord according to Eurocode 3, chord width wider than truss member, utilization ratio at 0.66.

APPENDIX D

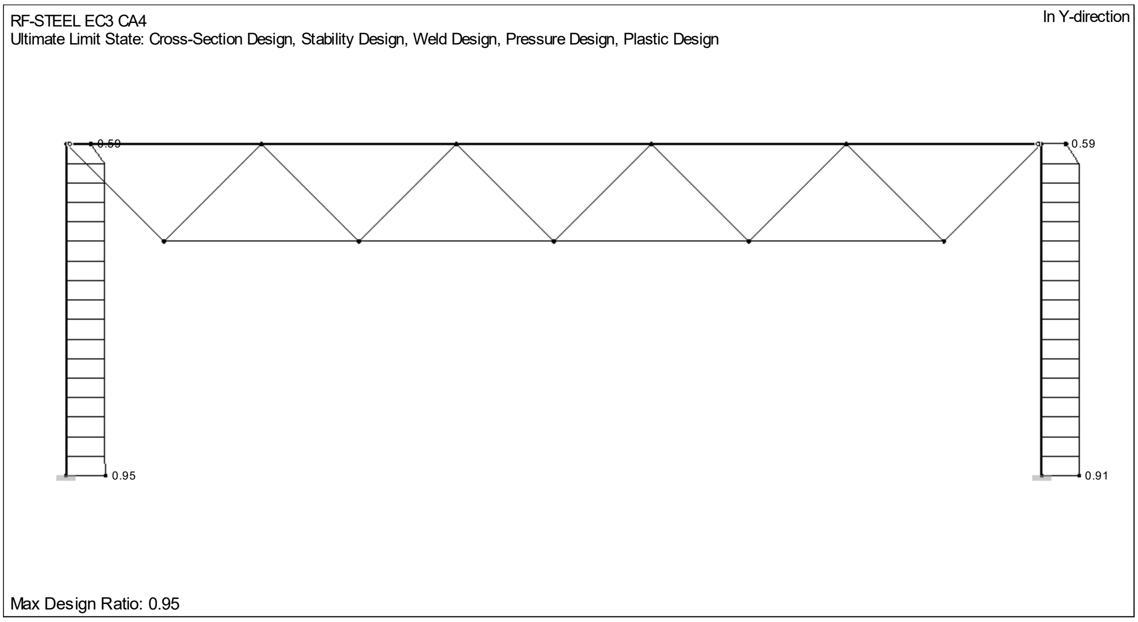


Figure 0-27 Optimization of columns, utilization ratio at 0.95.

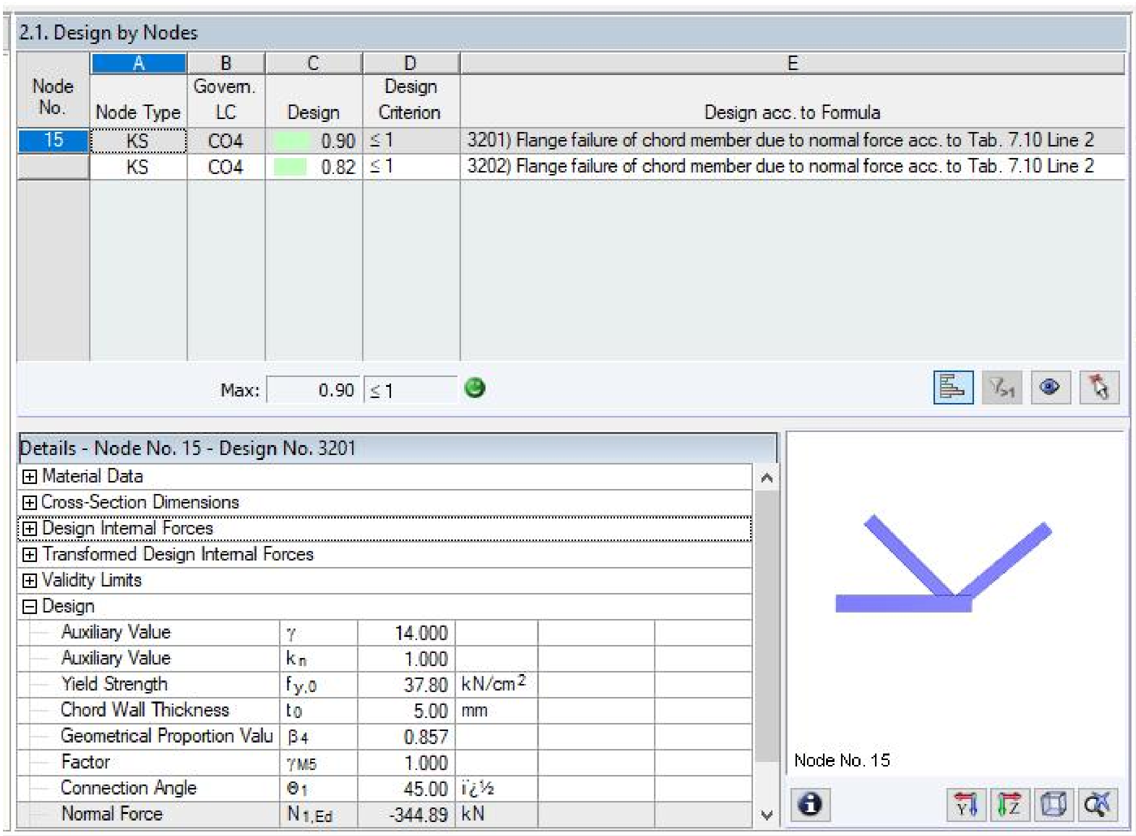
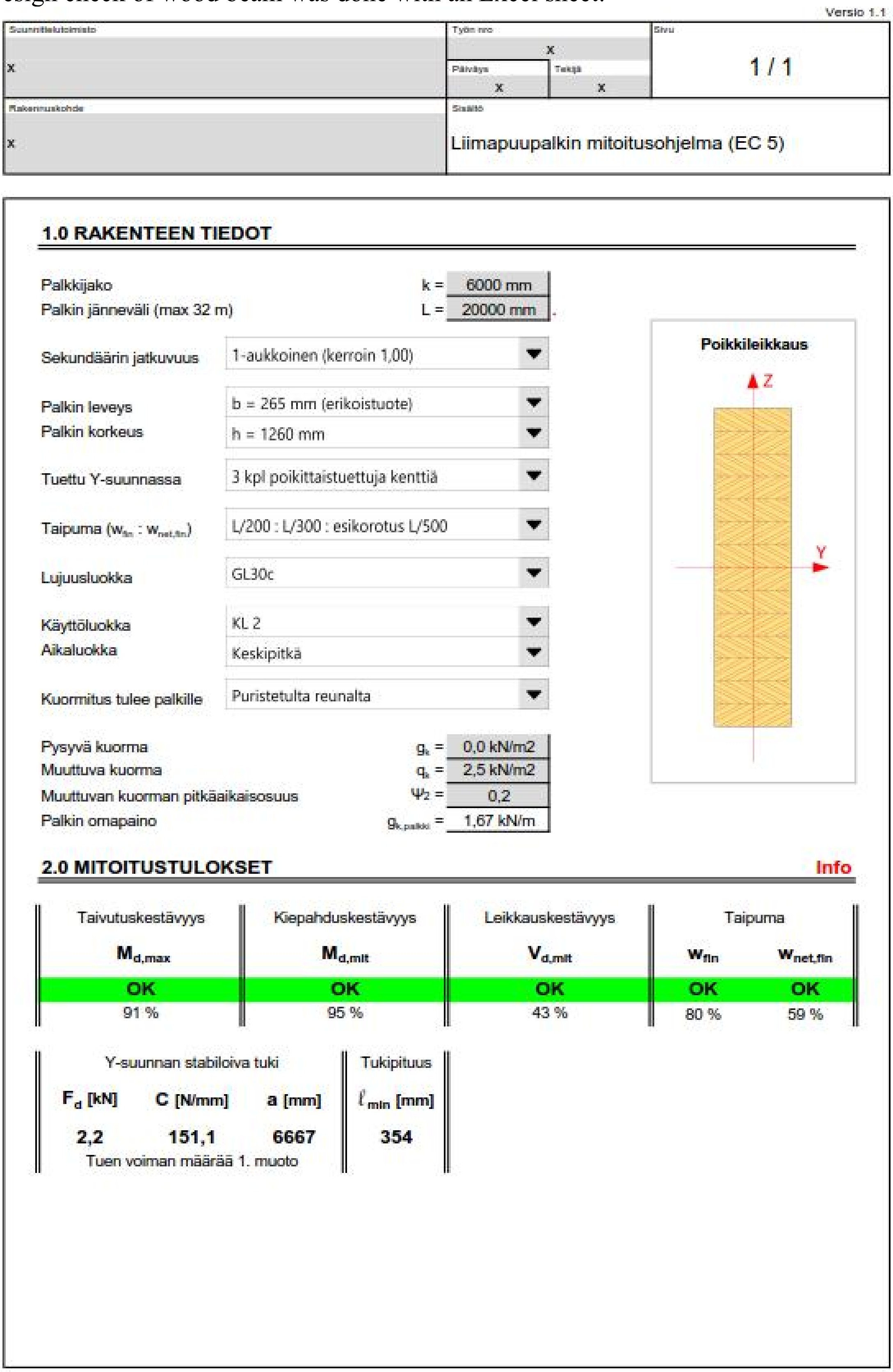


Figure 0-28 Checking of truss nodes, utilization ratio at 0.90.

APPENDIX E

Design check of a wood beam

Design check of wood beam was done with an Excel sheet:



Versio 1.1

Suunnittelutoimisto	Työn nro	Sivu
x	x	1 / 1
	Päiväys: x / Tekijä: x	
Rakennuskohde	Sisältö	
x	Liimapuupalkin mitoitusohjelma (EC 5)	

1.0 RAKENTEEN TIEDOT

Palkkijako	k =	6000 mm
Palkin jänneväli (max 32 m)	L =	20000 mm
Sekundäärin jatkuvuus		1-aukkoinen (kerroin 1,00)
Palkin leveys		b = 265 mm (erikoistuote)
Palkin korkeus		h = 1260 mm
Tuettu Y-suunnassa		3 kpl poikittaistuettuja kenttiä
Taipuma (w_{fin} : $w_{net,fin}$)		L/200 : L/300 : esikorotus L/500
Lujuusluokka		GL30c
Käyttöluokka		KL 2
Aikaluokka		Keskipitkä
Kuormitus tulee palkille		Puristetulta reunalta
Pysyvä kuorma	g_k =	0,0 kN/m2
Muuttuva kuorma	q_k =	2,5 kN/m2
Muuttuvan kuorman pitkäaikaisosuus	Ψ_2 =	0,2
Palkin omapaino	$g_{k,palkki}$ =	1,67 kN/m

2.0 MITOITUSTULOKSET Info

Taivutuskestävyys	Kiepahduskestävyys	Leikkauskestävyys	Taipuma	
$M_{d,max}$	$M_{d,mit}$	$V_{d,mit}$	w_{fin}	$w_{net,fin}$
OK	OK	OK	OK	OK
91 %	95 %	43 %	80 %	59 %

Y-suunnan stabiloiva tuki			Tukipituus
F_d [kN]	C [N/mm]	a [mm]	ℓ_{min} [mm]
2,2	151,1	6667	354
Tuen voiman määrää 1. muoto			

Figure 0-29 Excel sheet from Puuinfo A. (2020). Utilization ratio at 0.95.

APPENDIX E

Design check of a wood column

Design check of wood column was done with an Excel sheet:

Versio 1.1

Suunnittelutoimisto	Työn nro	Sivu
x	x	1 / 5
	Päiväys: x / Tekijä: x	
Rakennuskohde	Sisältö	
x	Liimapuupilarin mitoitusohjelma (EC 5)	

1.0 RAKENTEEN TIEDOT Info

Pilarin tyyppi	Mastopilari Z-suunnassa, Nivelpäinen pilari Y-suunnassa
Rasitussuunnat	Puristettu X-suunnassa - Taivutettu Z-suunnassa
Tuettu Z-suunnassa	Mastopilarilla ei tuentaa Z-suunnassa
Tuettu Y-suunnassa	Tuet päissä
Kuormituksen tyyppi Z-suunnassa	Tasainen kuorma
Kuormitus tulee pilarille Z-suunnassa	Puristetulta reunalta
Kuormituksen tyyppi Y-suunnassa	Ei kuormitusta Y-suunnassa
Kuormitus tulee pilarille Y-suunnassa	Ei kuormitusta Y-suunnassa
Poikkileikkauksen leveys	b = 240 mm (vakiotuote)
Poikkileikkauksen korkeus	h = 450 mm
Lujuusluokka	GL30c
Käyttöluokka	KL 2
Aikaluokka	Hetkellinen

Pilarin pituus	$L =$	6000 mm
Pilarin omapaino (MRT)	$g_{d,pilari} =$	3,73 kN
Normaalivoima X-suunnassa (MRT)	$N_{d,x} =$	241,0 kN
Momentti Z-suunnassa (MRT)	$M_{d,y} =$	43,0 kNm
Leikkausvoima Z-suunnassa (MRT)	$V_{d,y} =$	27,0 kN
Momentti epäkeskisyydestä Y-suunnassa (MRT)	$M_{d,z} =$	43,0 kNm
Leikkausvoima epäkeskisyydestä Y-suunnassa (MRT)	$V_{d,z} =$	27,0 kN

2.0 MITOITUSTULOKSET Info

Nurjahduskestävyys [Z]	Nurjahduskestävyys [Y]	Leikkauskestävyys [Z]	Leikkauskestävyys [Y]
$N_{d,x} + M_{d,y}$	$N_{d,x} + M_{d,z}$	$V_{d,y}$	$V_{d,z}$
OK	OK	OK	OK
80 %	72 %	12 %	12 %

Z-suunnan stabiloiva tuki			Y-suunnan stabiloiva tuki		
Fd [kN]	C [N/mm]	a [mm]	Fd [kN]	C [N/mm]	a [mm]
0,0 kN	0,0	-	0,0 kN	0,0	-
Tuet vain pilarin päissä (kiertymän estävä tuki)			Tuet vain pilarin päissä (kiertymän estävä tuki)		

Excel sheet from Puuinfo C, (2020). Utilization ratio at 0.80

APPENDIX F

Design of a reinforced footing

L	1500	mm	Foundation length
B	900	mm	Foundation width
h	650	mm	Foundation thickness
	0,9	m^3	Volume of footing
a	600	mm	Column width in L-direction
b	600	mm	Column width in B-direction
e_x	0	mm	Column eccentricity in L-direction
e_y	0	mm	Column eccentricity in B-direction
h_{column}	90	mm	Column height
G_{sw}	43,7	kN	Footing+soil self-weigth
d_{mss}	1000	mm	Top soil thickness
p_k	500	kN/m^2	Allowed soil pressure in SLS (ask GEO)
D	1650	mm	Depth of foundation

	Diam. Φ	Spacing		A_s	$A_{s,min}$	d
$A_{s,x}$	12	100	✓	1131	786	589
$A_{s,y}$	12	100	✓	1131	770	577

c_{nom}	✓ 55	mm			
$c_{min,dur}$	20	mm	E_s	200000	MPa
Δc_{dev}	20	mm	E_{cm}	31476	MPa
f_{ck}	25	MPa	f_{cd}	14,2	MPa
γ_c	1,5		f_{ctm}	2,6	MPa
f_{yk}	500	MPa	f_{yd}	434,8	MPa
γ_s	1,15		w_{lim}	0,30	mm
$\phi_{creep,eff}$	1,5		$w_{lim,x}$	0,42	mm
α_e	6,4		$w_{lim,y}$	0,42	mm
$\alpha_{e,eff}$	15,9				

Pressure distribution type ULS	Triangular
Pressure distribution type SLS	Triangular

φ'_k	34	°	Angle of friction
$\varphi'_{cv,k}$	30	°	Critical state angle of shearing
$\gamma_{mas,ip}$	22	kN/m^3	Weight density above foundation depth
$\gamma_{mas,ap}$	17	kN/m^3	Weight density below foundation depth

Bearing resistance calculation method: Calculate

Limiting effect = Kern

✓ **97 %**

	Action	Resistance	Utilization		CO
Overturning	-	-	✓ 33 %	EQU/ULS	1
Max ULS-pressure	183 kPa	-	-	ULS	
Bearing	177 kPa	-	✓ 21 %	ULS	1
Sliding	-	84 kN	✓ 30 %	ULS	1
Moment L	22 kNm/m	281 kNm/m	✓ 8 %	ULS	1
Moment B	1 kNm/m	275 kNm/m	✓ 1 %	ULS	1
Shear L	0 kN/m	205 kN/m	✓ 0 %	ULS	2
Shear B	0 kN/m	202 kN/m	✓ 0 %	ULS	2
Punching	-	-	✓ 1 %	ULS	
Anchorage L	-	-	✓ 6 %	ULS	
Anchorage B	-	-	✓ 4 %	ULS	
SLS-pressure	179 kPa	500 kPa	✓ 36 %	SLS-CH	101
Stresses L	22 kNm/m	190 kN/m	✓ 11 %	SLS-CH	101
Stresses B	1 kNm/m	186 kN/m	✓ 1 %	SLS-CH	101
Ellipse	-	-	✓ 24 %	SLS-CH	101
Crack width L	22 kNm/m	194 kN/m	✓ 11 %	SLS-QP	201
Crack width B	1 kNm/m	170 kN/m	✓ 1 %	SLS-QP	201
Stresses L	22 kNm/m	208 kN/m	✓ 8 %	SLS-QP	201
Stresses B	1 kNm/m	260 kN/m	✓ 1 %	SLS-QP	201
Kern	-	-	✓ 97 %	SLS-QP	201

LOAD COMBINATION ARE TO BE INPUT IN THE TABLES BELOW

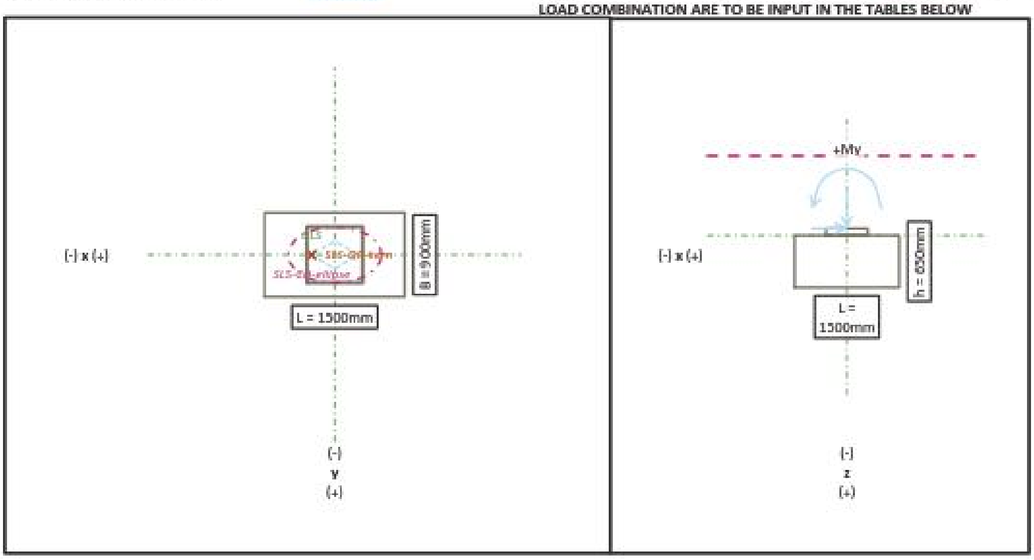


Figure 0-30 Design according to Eurocode 2. Footing checked for 19 cases, Utilization ratio at 0.97.

APPENDIX G

Design of semi-rigid frames

Iterative process started with modeling of RFEM model. The moment, shear force and axial force were copied from the frame model and imported to IdeaStatica joint model. In the joint model we can see reactions in a node Figure 0-31.

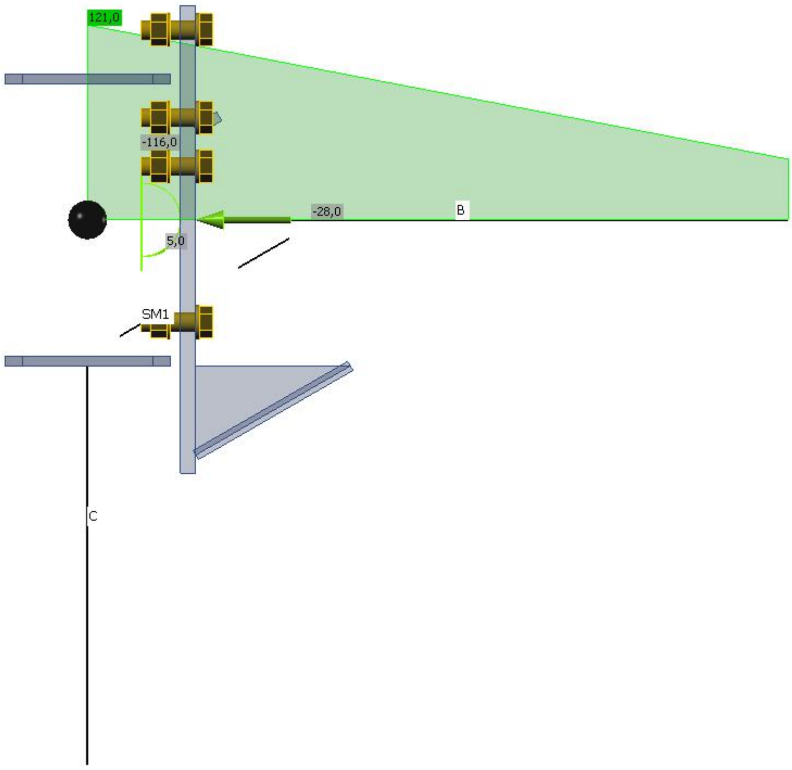


Figure 0-31 Nodal forces in IdeaStatica 10.1. Moment, shear force and axial force implied to the black node, which presents the intersection of beam's and column's center line. Results match the nodal forces in Dubal RFEM model

After initial guess for the connection, IdeaStatica calculates if the members in the model can endure the forces. In a case where a component fails, it highlights it with red, see Figure 0-32. If a different configuration does not fail, then the member is highlighted as green, see Figure 0-33.

Short list in left upper corner describes the utilization ratio of plates, bolts, and welds. Analysis refers to how many of the verifications the program was able to check. If the program can calculate the stiffness and the deflection of the connection, the values can be updated in the RFEM model, see Figure 0-34.

APPENDIX G

Iteration process of semi-rigid frame

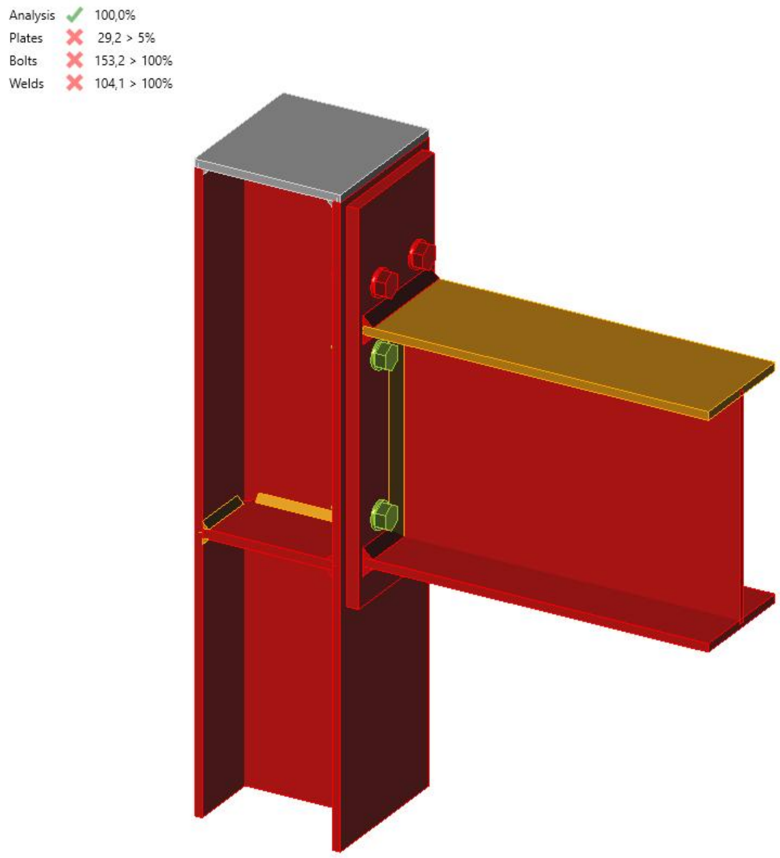


Figure 0-32 Failing connection in IdeaStatica 10.1

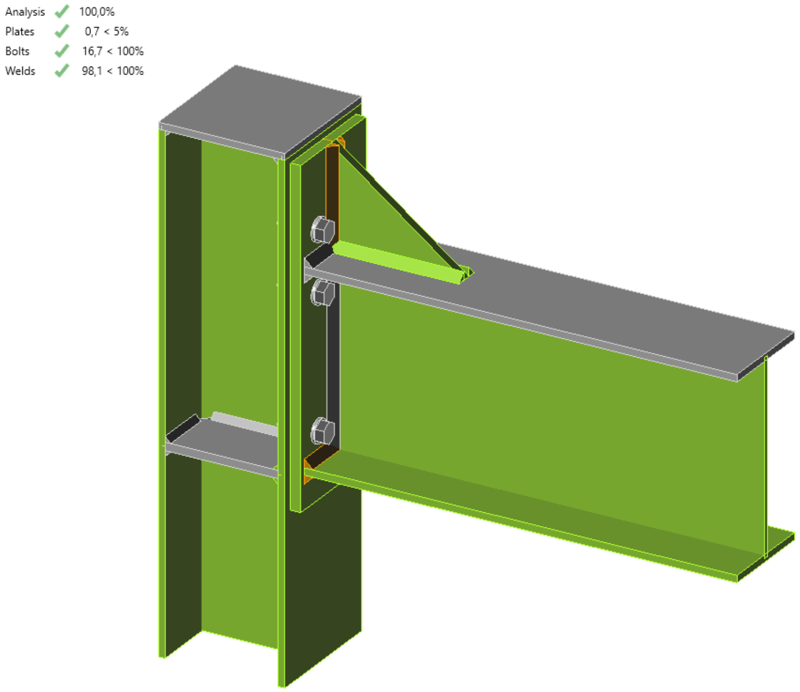


Figure 0-33 Working connection with stiffness of 62.5 MNm/rad

APPENDIX G

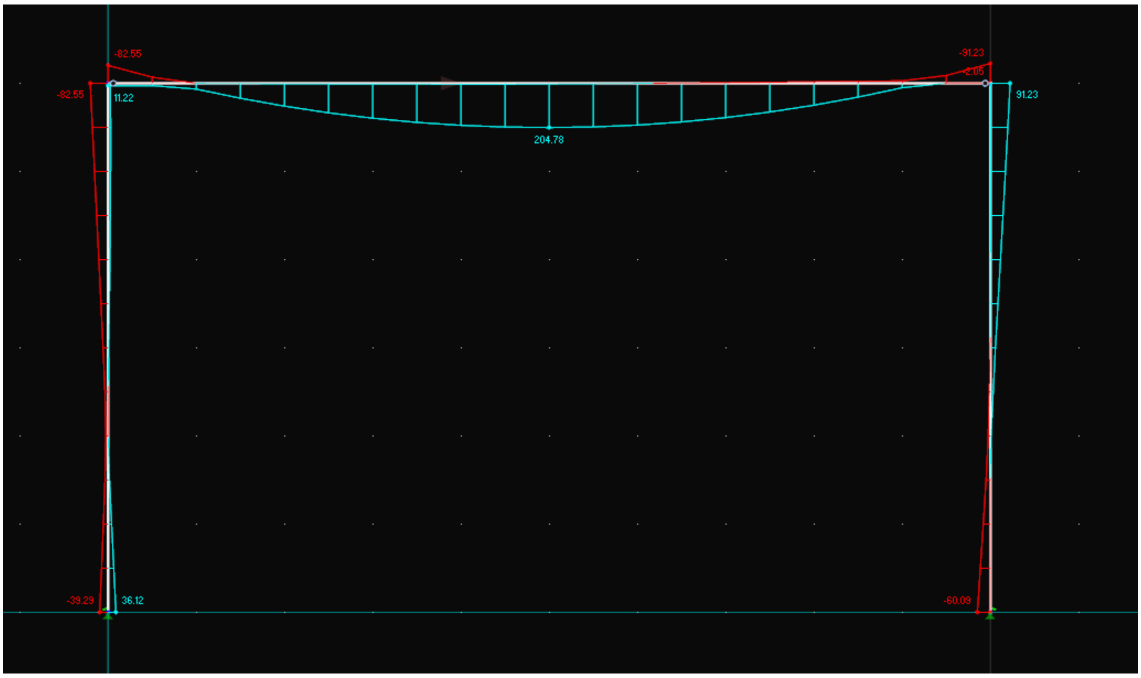


Figure 0-34 After defining the stiffness of the joints in the model. Frame resulted with mid-span moment of 204 kNm and corner moment of 91 kNm. Connection is required to have a higher stiffness.

In this example, the initial connection is not stiff enough, therefore moment in the mid span of the beam is too big relative to the end of the beam. Therefore, a different configuration of connection is designed to achieve a higher stiffness Figure 0-35.

APPENDIX G

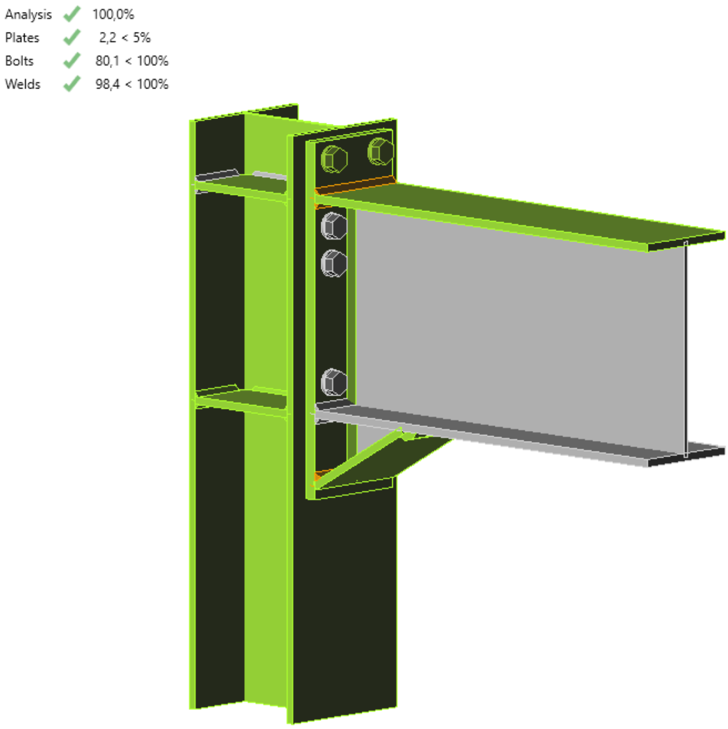


Figure 0-35 Increased connection stiffness to 92.0 MNm/rad

The second configuration achieves stiffness of 92 MNm/rad which is then updated into the RFEM model. This time moment in midspan is equal to 166 kNm, which is less than 190 kNm from rigid beam to column connection and smaller than 295 kNm from pinned beam-to-column connection Figure 0-36.

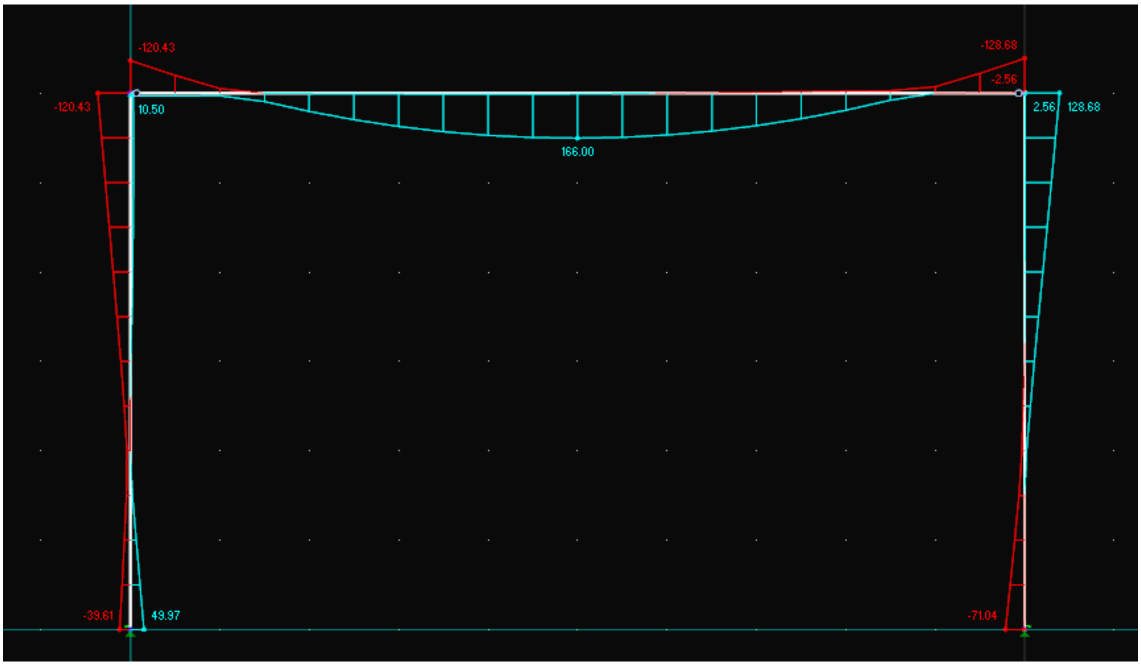


Figure 0-36 Second iteration resulted with mid-span moment of 166 kNm and corner moment of 129 kNm.